Variations in Winter Surface High Pressure in the Northern Hemisphere and Climatological Impacts of Diminishing Arctic Sea Ice

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by

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VARIATIONS IN WINTER SURFACE HIGH PRESSURE IN THE NORTHERN HEMISPHERE AND CLIMATOLOGICAL IMPACTS OF DIMINISHING ARCTIC SEA ICE

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This study explores the role Arctic sea ice plays in determining mean sea level pressure and 1000 hPa temperatures during Northern Hemisphere winters while focusing on an extended period of October to March. This is accomplished by investigating two regions of the same size and comparable climatic zones and elevations in the Northern Hemisphere. A breakdown of 29 years of reanalysis data into average monthly values, anomalies, trends, and comparisons between regions serves as current data to compare with a computer model control run. Ensuring the control run accurately models current atmospheric patterns, altering the model inputs to have no permanent Arctic sea ice will then show what winters could look like in the Siberian and Canadian regions if Arctic sea ice continues to diminish. The results for the reanalysis show that the Siberian region has higher MSLP and lower 1000 hPa temperatures than the Canadian region. The control run accurately captures the seasonal cycle from the reanalysis, except the values were offset slightly. Expected conditions associated with no sea ice would be warmer temperatures and lower pressures, and this situation is reflected in the results from the no sea ice run for the Canadian region. However, the no sea ice run results indicate stronger pressures and colder temperatures in the Siberian region, particularly from January to March.

DEDICATION

I would like to dedicate my thesis to my fiancé Corey Boe. Thank you for being willing to put our future on hold so that I could continue my education.

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Chapter 1. Introduction

Cohen and Entekhabi (1999) postulate that cooling caused by early season (October through December) snowcover is a dominant force in Northern Hemisphere climate variability. According to Lockwood (1979), wintertime high pressures in Siberia usually form over areas where snow thickness is more than 50 cm and the snowcover duration exceeds 200 days. If snowcover plays such an important role, one can assume that Arctic sea ice also is an important factor in Northern Hemisphere winter conditions. This study analyzes current Northern Hemisphere winters for two regions and, through a global climate model, attempts to forecast 1000 hPa temperature and mean sea level pressure changes that could occur from the continued decline of Arctic sea ice coverage.

The motivation of this study is to investigate how winters in the Northern Hemisphere will change if permanent Arctic sea ice does not exist. This will be done by focusing on mean sea level pressure and 1000 hPa temperature patterns in a Siberian and Canadian study region. To accomplish the goal of this study, a global climate model is run under conditions of open water, focusing on an extended winter season from October to March in the Northern Hemisphere. In order to evaluate the magnitude of the results from the no sea ice model run, there must be something to which it can be compared. A control run is used to represent current winter conditions for both regions, except there needs to be a way to make sure the control run is accurately modeling current patterns. This accuracy check is done through comparing control run data to a climatology of reanalysis data. 29 years of reanalysis data are summarized into average monthly values for pressure and temperature, as well as anomalies and trends. These values are grouped into individual months, a winter (December, January, and February) season, and extended study period (October to March). The data are also viewed long-term within each region as well as compared between regions.

Chapter 2. Background

2.a. Study Regions

The overall climate in the Canadian region is cold and lacks a dry season (Df) according to the updated Köppen-Geiger climate classification (Figure 1) done by Peel et al. (2007). The northern part of the Canadian region can be further subdivided because of cold summers (Dfc). The rest of the Canadian region has warm summers (Dfb). During the winter, temperatures in the Canadian region are below freezing from November to March, with October temperatures of 6.1 °C. The western edge of the Canadian study region, due to the Rocky Mountains' influence also creates a small west to east climate variation in the Canadian region.

The presence of the Rocky Mountains on the western boundary of the Canadian region causes the greatest elevations to occur in the southwest corner, ranging from 1500-2500 meters above sea level (Figure 2a) to 500-1000 meters in a northeast pattern (GLOBE Task Team and others 1999). Besides the elevations associated with the Rocky Mountains, the rest of the Canadian region has elevations of less than 500 meters above sea level.

Similar to the Canadian region, Peel et al. (2007) also shows northern parts of the Siberian region having a cool continental subarctic climate. Northern Siberia's climate is mostly cold, without a dry season, and a cold summer (Dfc), and there is a small area on its eastern edge with extremely severe winters (Dfd). The Dfd climate is still continental and subarctic, yet temperatures can drop below -38 °C in the coldest month. Eastern

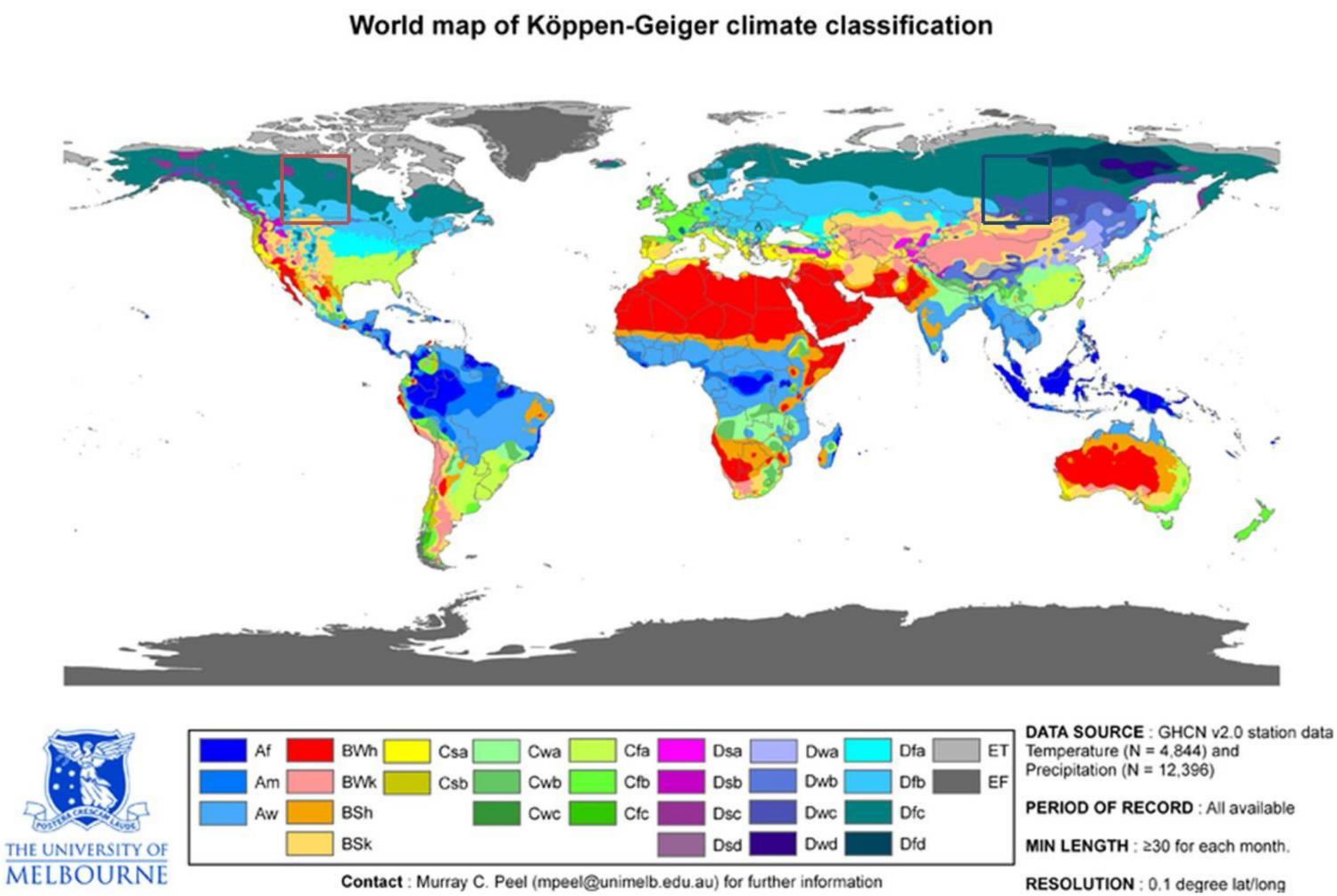


Figure 1: Köppen-Geiger Climate Classification with Canadian region (red) and Siberian region (blue) outlined. (Peel et al. 2007)

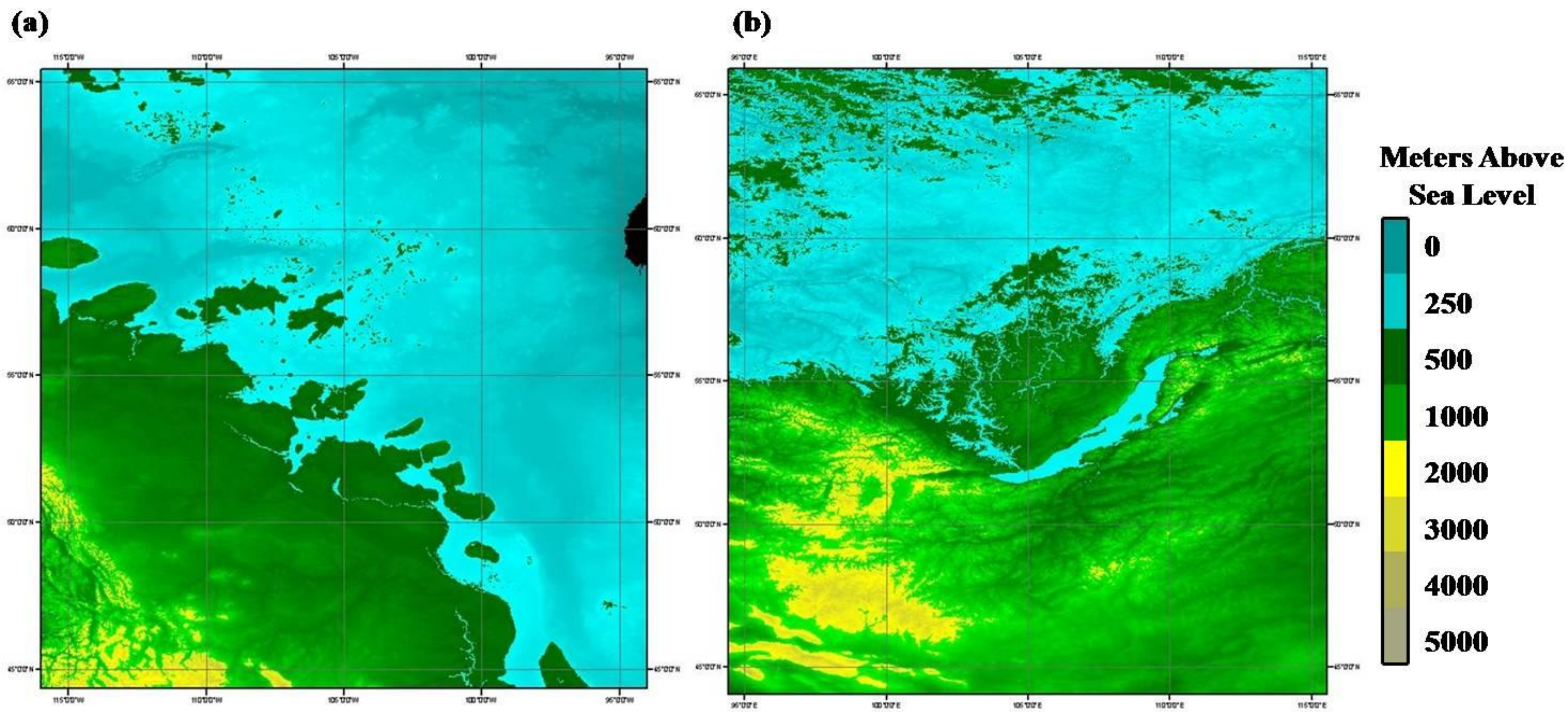


Figure 2: Study region elevations in the (a) Canadian region and (b) Siberian region. (GLOBE Task Team and others 1999)

Siberia is the only place on earth this climate zone exists. Siberia's southern region is mostly cold with dry winters and cold summers (Dwc). Other parts of southern Siberia are influenced by the Altai Mountains, with small arid, steppe, cold climate areas (Bsk). Wintertime temperatures in the Siberian region are generally colder than in the Canadian region, yet are similar in that October temperatures are the only month (October to March) that are above freezing.

Unlike in the Canadian region, the mountains in the Siberian region are on the southern boundary of the region (Figure 2b). The highest elevations of the Altai Mountains within the Siberian region are in the southwest corner, averaging 2000-3000 meters above sea level (GLOBE Task Team and others 1999). Southern areas of the Siberian region also have small valley areas between 800-1500 meters. Otherwise, elevations in the largest part of the Siberian region are extremely flat, with elevations less than 500 meters above sea level.

2.b. Previous Work

High pressure conditions that dominate Siberian winters typically form in October and persist through April. This cold, dense, shallow air mass dominates low-level circulation in winter (Panagiotopoulos et al. 2005) and is thermodynamically forced. Surface high pressure may also be created by dynamic forcing through air descending from aloft. High pressure systems can be influenced by either forcing mechanism or a combination of the two. The frequency and strength of high pressure systems in this region play an important role in modulating daily temperature variations during the winter months (Gong et al. 2004). The existence and behavior of this semi permanent high pressure system, commonly referred to as the Siberian High, is well documented. In January, the center of the Siberian High exists from around 40-55 °N and 90-115 °E (Kutzbach 1970). There is no mention of a matching system in the Western Hemisphere, although there is clear evidence of high pressure in central Canada and the northern plains of the United States approximately 40-70 °N and 90-120 °W (Figure 3). This “Canadian High” is 12-16 hPa weaker than the Siberian High and is about the same latitude and a mirror image of the Siberian High.

Eurasian snow cover forces the early winter season (September, October, and November) air circulation and is a major thermodynamic forcing in the Siberian High’s growth and expansion (Cohen et al. 2001). The cooling effect of snowcover is associated with a strengthened and more expansive Siberian High (Cohen and Entekhabi 1999). This cooling effect comes from a high albedo, reflecting a greater percentage of the sun’s incoming rays than any other type of surface. Asia is the largest land mass on Earth, so a cooling effect from snow cover has the potential to affect the entire Northern Hemisphere’s winter season.

While most work on the Siberian High focuses on a large geographic region (Gong et al. 2001; Gong and Ho 2002; Gong et al. 2004; Panagiotopoulos et al. 2005; Sahsamanoglou et al. 1991; Wu and Wang 2002), others have described the Siberian high behavior via a single point centered at 67.5 °N and 150 °E (Cohen et al. 2001) or 47 °N and 90 °E (Takaya and Nakamura 2005a, b). However, using data from only one station could have significant variations, so defining a center of action effectively gets rid of

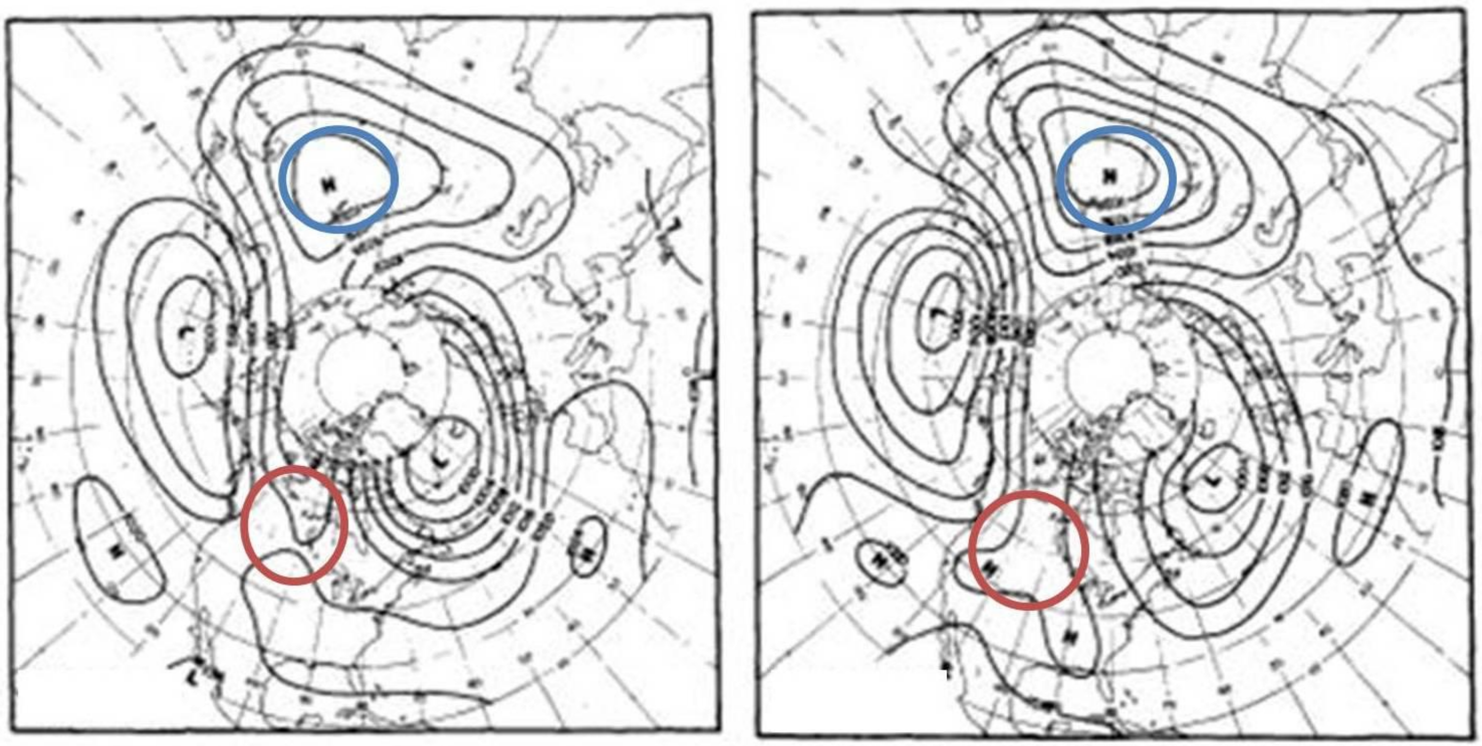


Figure 3: January mean sea level pressure patterns from 1903-1917 (left) and 1955-1969 (right). Canadian high (red) and Siberian high (blue) circled. Adapted from Kutzbach 1970.

potential errors at single data points. A strictly numerical study of the Siberian High by Sahsamanoglou et al. (1991) used a region of 40-55 °N and 90-110 °E and found that the central pressure of the Siberian High is negatively correlated with longitude and positively correlated with latitude. The mean monthly values for the Siberian High central pressure grows from 1027.5 hPa in October to a maximum of 1037.5 hPa in January, and then slowly declines thereafter through March. The minimum value for any month from October to March in their 1873-1988 dataset is 1022.6 hPa, still a strong high pressure value. With the exception of March and October (transition months between seasons), the central pressure of the Siberian High shows an increasing trend from 1930-1970, and decreasing after 1970 (Sahsamanoglou et al. 1991).

The effects of the Siberian High reach a much greater geographical area than the main domain in north central Siberia. The Siberian High truly has hemispheric impacts, some of which last through winter into the following spring and fall. Panagiotopoulos et al. (2005) defined a Siberian High Index (SHI) from mean sea level pressure measurements within a grid of 40-65 °N and 80-120 °E. This study addresses how long-term Siberian High variability relates to extratropical variability elsewhere in the Northern Hemisphere. When the Siberian High starts to form in October, extratropical cyclones are blocked and diverted farther north over the Kara-Laptev Seas and fewer storms pass over Siberia, decreasing temperature advection over the Siberian region. Consequently, a weakened Siberian High leads to more storms passing over the region with warm air advection.

Several studies have also shown how the Siberian High relates to other atmospheric phenomena, such as the Arctic Oscillation (Gong et al. 2004; Wu and Wang 2002), East Asian Winter Monsoon (EAWM) (Gong et al. 2001), and recent climate change in China (Gong and Ho 2002; Gong and Ho 2004). Gong et al. (2004) studied a small central region of the Siberian High: 45-55 °N and 90-110 °E, though this latitudinal range is too small to capture the behavior of the Siberian High effectively. Using a larger region, a Siberian High Index/Central Intensity (SHI/SHCI) was defined as the regional mean sea level pressure over an area 40-60 °N and 70-120 °E (Gong et al. 2001; Gong and Ho 2002). Strengthened SHCI values correspond with colder than usual surface temperatures and decreased precipitation over Asia (Gong and Ho 2002). Wu and Wang (2002) found that the Arctic Oscillation and Siberian High both independently affect the EAWM. To determine the Siberian High's effects on the EAWM, Wu and Wang (2002) constructed a Siberian High Index of the average sea level pressure for the region of 40-60 °N and 80-120 °E. The Siberian High Index and EAWM were found to be highly correlated, implying that the Siberian High can regulate the intensity of the EAWM. The effects of the Siberian High on the EAWM can be seen in the strong northwesterly winds from the east side of the Siberian High, bringing with them intensely cold air into East Asia (Gong et al. 2001).

The effects of the Siberian High on the winters of Asia and Europe are numerous and have been studied in detail. For example, the Siberian High can explain about 43.6% of the wintertime temperature variance in China (Gong and Wang 1999). However, the effects of Siberian high pressure on North America are slightly harder to visualize, even though the Siberian High occasionally does reach North America.

When sea level pressure anomalies first appear over Siberia in October, this extremely dense cold air forms a shallow layer near the surface (Cohen et al. 2001). It grows west, following the ground's snow coverage. If high amounts of snow cover the ground, air temperatures are colder, resulting in increased divergence and a stronger Siberian High. The westward expansion of the Siberian High is limited by high topography and a maritime North Atlantic influence in central and western Asia (Cohen and Entekhabi 1999). As the Arctic Ocean freezes, the Siberian High expands northward over the North Pole and into North America. This expansion of the Siberian High forces the Icelandic Low to move south, creating conditions similar to the negative phase of the Arctic Oscillation. If snowcover is limited and the Siberian High is not large enough to cross over the pole, the Icelandic High is free to move northward, as observed during the positive phase of the Arctic Oscillation. Cohen et al. (2001) concluded that the behavior of early winter snowfall could be used loosely to predict the subsequent development of the Siberian High and its impact on winters in the Northern Hemisphere.

While no study exists on a Canadian High, all of the previous studies on the Siberian High analyze past data to explain patterns and connections, yet no attempt to predict how pressure or temperature within the Siberian High or Canadian High might change in the future. This research is vital, especially with the unforeseen effects of continued global warming and diminishing Arctic sea ice.

Chapter 3. Methods

This study investigates winter mean sea level pressure (MSLP) and 1000 hPa temperature patterns for a Siberian and Canadian region through long-term, seasonal, and monthly averages, anomalies, trends, and investigates relationships between the two locations. It is difficult to find two geographic regions that share the exact climate characteristics, yet there are only a few small differences between the Siberian and Canadian study regions. Observations for the two regions are compared to global climate model (GCM) output for the same regions. The GCM is then altered to see how future climate change might affect mean sea level pressures and 1000 hPa temperatures within these study regions.

3.a. Study Regions

The Siberian region is defined as the area within 45-65 °N and 95-115 °E (Figure 4). High pressure systems in Siberia sometimes extend south of 40 °N, however that area has very high terrain and difficulties arise when extrapolating surface pressure data down to sea level (Panagiotopoulos et al. 2005), so 45 °N is used as the most southern boundary.

For comparison, a similar domain of equal size was set for the Canadian region as 45-65 °N and 95-115 °W (Figure 4). The western boundary is the Rocky Mountains and the eastern boundary is Hudson Bay. North of 65 °N is the Canadian Arctic archipelago, where the amount of water and the land proximity to it would not provide enough of a temperature contrast conducive for the formation of a high pressure system, especially with the possibility of continued sea ice decline as a result of global warming. Canada's

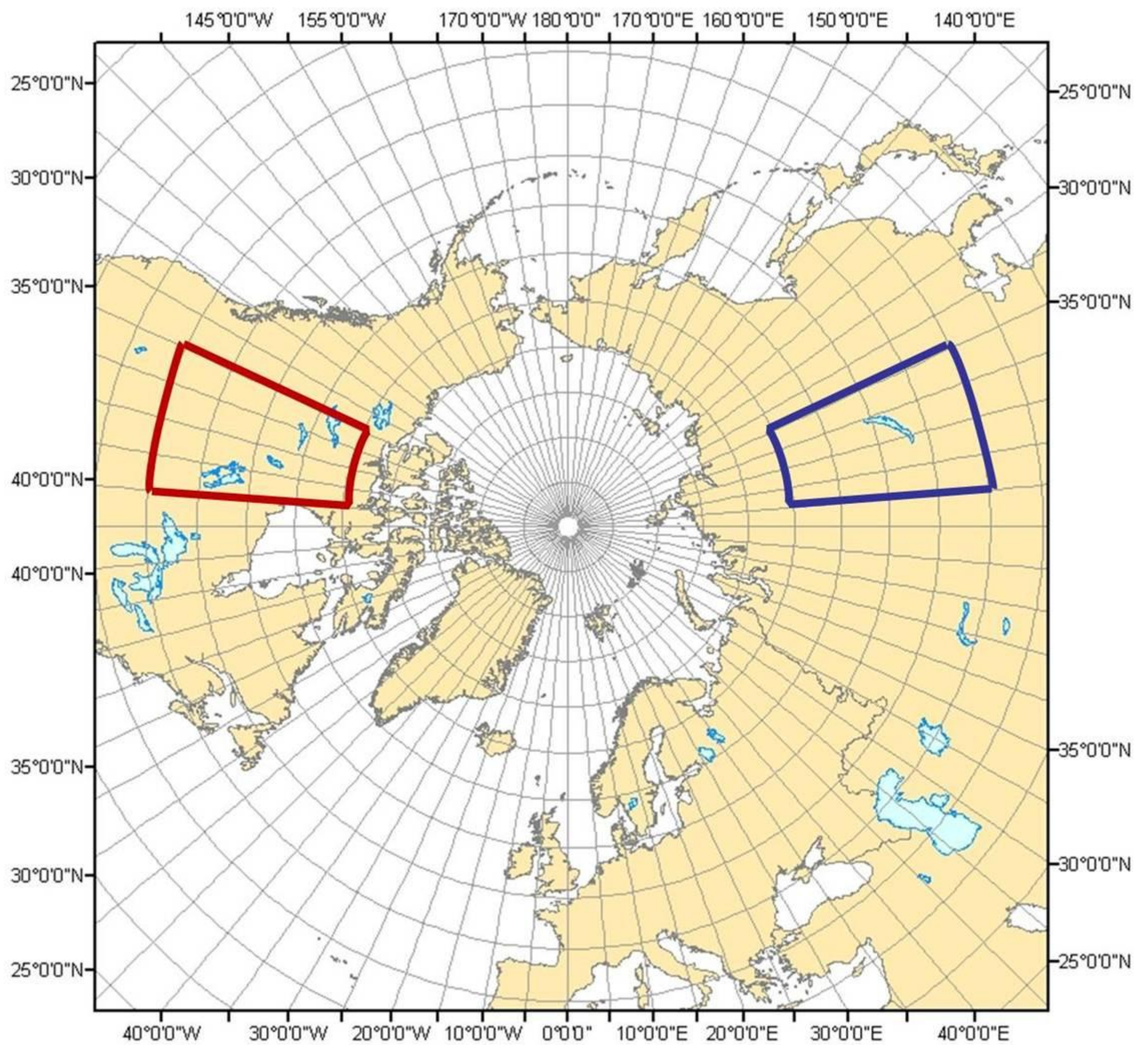


Figure 4: Study Areas: Canadian region (left, in red) and Siberian region (right, in blue).

southern border is near 50 °N, with the southern provinces being mostly flat and the largest continuous land mass in the country. To maintain the same area size for both locations and since there is similar geography from 50-45 °N in the United States Northern Plains states, that area is included in the Canadian region as well.

Since the Siberian and Canadian regions occupy the same latitudinal areas, both regions receive the same amount of solar radiation, which is an important influence on a location's climate. The study regions also have the same longitude spacing so that they both take up the same area. Keeping the same constraints on both regions will make comparisons between the two more realistic.

3.b. NCEP-NCAR Reanalysis II Data

This study utilizes NCEP-NCAR Reanalysis II (Kanamitsu et al. 2002) monthly mean sea level pressures (MSLP) and monthly mean 1000 hPa temperatures for 1979-2008. The NCEP-NCAR Reanalysis II data were obtained from NOAA/OAR/ESRL PSD, in Boulder, Colorado, USA (NOAA/OAR/ESRL PSD 2009). This study refers to the NCEP-NCAR Reanalysis II data simply as reanalysis.

The study period uses October through March data in an extended winter season analysis for the years 1979-2008. Numerical averages were computed for the study period each month for MSLP and 1000 hPa temperature over both domains. The months of December, January, and February (hereafter: DJF) are used to define the winter season. Each year's winter season comes from the December year: December 1979, January 1980, and February 1980 comprise the 1979 winter season. A monthly, winter

(DJF), and long-term (October through March) average were calculated for each parameter. For each average value, anomalies were obtained to make it easier to analyze variations. Trend analysis was also performed.

3.c. Computer Model Data

The GCM data used in this study came from a Community Atmospheric Model version 3.0 (CAM) model run (Collins et al. 2006). This GCM model was developed at the National Center for Atmospheric Research, and includes an optional combination of a slab ocean and thermodynamic sea ice model. Changes in the dynamics and physics of CAM3.0 with respect to previous versions create improved simulations of the surface hydrological cycle and temperatures at the surface and in upper levels (Hack et al. 2006). These improvements should create more reliable conditions, which can be used to create a more accurate picture of future climate changes.

In order to identify future climate changes with confidence, it is important that a model can accurately depict current weather patterns first. Twelve months of current atmospheric conditions forced the start-up of the model, which continued to run for fifteen years. Fifteen years of run-time allows the model to equilibrate and settle on values for each month to create an accurate yearly pattern. Data from after the start-up were averaged together to create a mean monthly value for MSLP and 1000 hPa temperature. These single values will be compared to the 29 year reanalysis monthly, winter, and long-term means to see how closely the model simulated actual patterns for the two study regions.

In order to simulate climate variations under a warmer scenario, the global climate model was also run under conditions of no permanent (year-round) Arctic sea ice. Areas of current sea ice, including Hudson Bay, were forced to remain as open water at 0 °C. Open water has a completely different set of climate feedbacks than sea ice and these feedbacks could be responsible for future climate change. Since water has a higher heat capacity than land, areas of open water are able to release heat through the winter and insulate the land, dampening the otherwise Arctic winter weather. Correlating this altered climate state to the GCM control run and reanalysis data can show possible future changes for pressure and temperature within the Siberian and Canadian study regions.

Chapter 4. Results

4.a. Reanalysis Data

Mean sea level pressure (MSLP) and 1000 hPa temperature from the reanalysis data for 1979-2008 are investigated for the Siberian and Canadian study regions to determine normal conditions, trends, and anomalies. Analysis and trends are computed for a six month extended season (October to March), the winter (December, January, February), as well as individual monthly values.

4.a.1. Extended Study Period (October to March)

4.a.1.i. Mean Sea Level Pressure (MSLP)

The average MSLP for the Siberian region increases from October to a peak in January and decreases through March (Figure 5a). The MSLP range for any month in the Siberian region can be as low 7 hPa in October or as much as 13-15 hPa for December through February with December the most variable month (Table 1). The MSLP pattern for the Canadian region is slightly different, peaking in February instead of January (Figure 5a and Table 2). The monthly MSLP range for the Canadian region is greater than in the Siberian region, with an 11-14 hPa range from November through March. Pressure values in October are less variable than the other months, staying within a 7.5 hPa range.

Regions that are mirror images of each other across hemispheres could have positive correlations of MSLP or 1000 hPa temperature, meaning that a change in one region could have the same change in the other region. For example, pressure values,

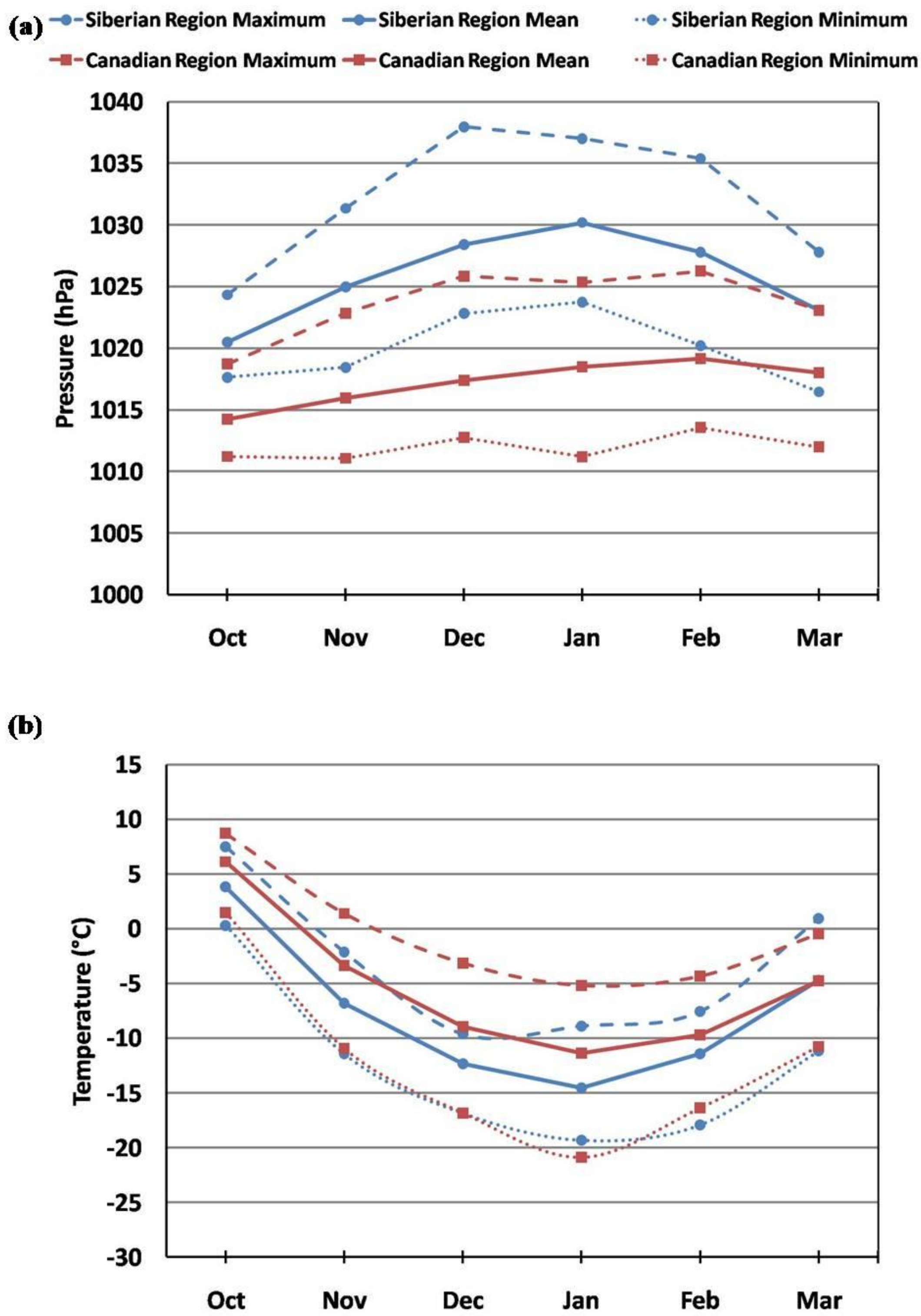


Figure 5: Extended study period (October to March) for (a) MSLP and (b) 1000 hPa temperature for the two study regions.

Table 1: Siberian Region Monthly MSLP (hPa)

	Mean	Maximum	Minimum	Range	Std. Dev.
October	1020.5	1024.3	1017.6	6.7	2.0
November	1025.0	1031.4	1018.4	13.0	2.5
December	1028.4	1038.0	1022.8	15.2	3.6
January	1030.2	1037.0	1023.8	13.2	2.9
February	1027.8	1035.4	1020.2	15.2	3.5
March	1023.1	1027.8	1016.5	11.3	2.4
Winter	1028.8	1033.1	1025.4	7.7	2.0

Table 2: Canadian Region Monthly MSLP (hPa)

	Mean	Maximum	Minimum	Range	Std. Dev.
October	1014.2	1018.7	1011.2	7.5	1.9
November	1016.0	1022.8	1011.1	11.7	2.6
December	1017.4	1025.8	1012.8	13.0	3.3
January	1018.5	1025.4	1011.2	14.2	3.6
February	1019.2	1026.3	1013.6	12.7	2.8
March	1018.0	1023.1	1012.0	11.1	2.5
Winter	1018.3	1021.3	1015.7	5.6	1.6

when correlated between regions, start positively correlated in October (0.18) and end negatively correlated (-0.34) in March (Figure 6 and Table 3). A positive correlation implies that a MSLP change in one region will have the same type of change in the other region, and that a negative correlation will cause opposite changes between regions. The timing of peak mean sea level pressure in each region can partially explain the correlation switch. For example, in February, MSLP in the Siberian region is weakening, while MSLP in the Canadian region is still increasing. In March, however, when MSLP is decreasing in both regions, the correlation is still negative. A winter correlation for Siberian and Canadian pressure values is 0.07. While these correlation values are not large, they do illustrate a link or relationship between the Siberian and Canadian regions.

4.a.1.ii. 1000 hPa Temperature

Overall, 1000 hPa temperatures have smaller ranges than MSLP for both the Siberian region and Canadian region for the entire period studied (Figure 5b). The Siberian region is above freezing only in October (3.8 °C), and reaches its coldest temperature in January (-14.6 °C) when the MSLP is the highest (Tables 1 and 4). Temperatures are warmer in March, yet still below freezing. Early season (October, November, and December) 1000 hPa temperature variability in the Siberian region is less than in the latter stages of winter (January, February, March): 7-9 °C compared to 10-12 °C (Table 4). Temperatures for the Canadian region follow the same pattern as those for the Siberian region, although they are warmer by 2-3 °C (Figure 5b and Table 5). The average March temperatures, however, are the same for both regions. Even though minimum average 1000 hPa temperatures for both regions are within 1 °C

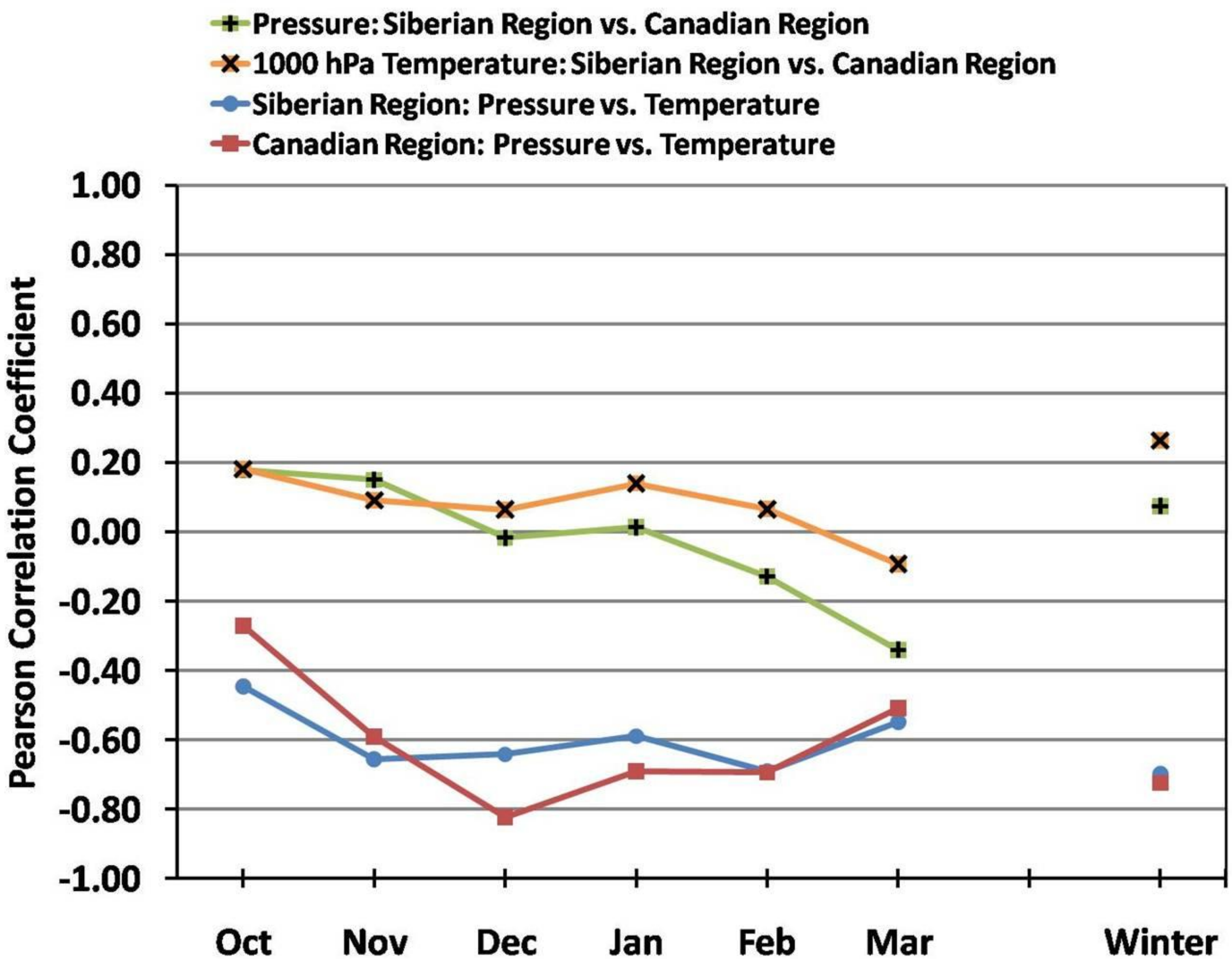


Figure 6: Pearson Correlations.

Table 3: Reanalysis Pearson Correlations

	Siberian Region vs. Canadian Region		MSLP vs. 1000 hPa Temperature	
	MSLP	1000 hPa Temperature	Siberian Region	Canadian Region
October	0.18	0.18	-0.45	-0.27
November	0.15	0.09	-0.66	-0.59
December	-0.02	0.06	-0.64	-0.82
January	0.01	0.14	-0.59	-0.69
February	-0.13	0.07	-0.69	-0.69
March	-0.34	-0.09	-0.55	-0.51
Winter	0.07	0.26	-0.70	-0.72

Table 4: Siberian Region Monthly 1000 hPa Temperature (°C)

	Mean	Maximum	Minimum	Range	Std. Dev.
October	3.8	7.5	0.3	7.2	1.7
November	-6.8	-2.2	-11.4	9.2	2.6
December	-12.3	-9.6	-16.9	7.3	2.3
January	-14.6	-8.9	-19.3	10.4	2.9
February	-11.4	-7.6	-17.9	10.3	2.8
March	-4.7	0.9	-11.2	12.1	2.9
Winter	-12.8	-9.6	-17.1	7.5	1.9

Table 5: Canadian Region Monthly 1000 hPa Temperature (°C)

	Mean	Maximum	Minimum	Range	Std. Dev.
October	6.1	8.7	1.5	7.2	1.6
November	-3.4	1.4	-11.0	12.4	3.1
December	-9.0	-3.2	-16.8	13.6	3.8
January	-11.4	-5.2	-20.9	15.7	3.8
February	-9.7	-4.4	-16.4	12.0	3.2
March	-4.8	-0.5	-10.8	10.3	2.7
Winter	-10.0	-5.7	-14.3	8.6	2.2

of each other, the overall range for the Canadian region is greater than the Siberian region, caused by the dissimilarity of maximum temperatures between regions.

Temperature correlations between the two study regions are not as large as for MSLP. For example, temperatures in the Siberian region correlate at 0.18 with October temperatures in the Canadian region (Figure 6 and Table 3). The October temperature correlation is the highest monthly correlation for temperature, and values decrease each month afterward until it becomes negative in March (-0.09). When viewed over the entire winter, temperatures for the two regions correlate at 0.26. These correlation values indicate that the Siberian region and Canadian region temperatures influence each other, although the small values imply that other variables may influence the behavior of temperature as well.

4.a.1.iii. Summary

The geographical separation between both study regions leads to small correlation values. Larger correlations are seen when investigating relationships within each region (Figure 6). On a monthly basis, correlations of MSLP and 1000 hPa temperature are negative for each region (Table 3). Negative correlations imply an inverse relationship between pressure and temperature, for example, increased pressure and decreased temperature. For the Canadian region, pressure and temperature correlate at -0.27 in October, decrease to -0.82 in December, and increase to -0.51 in March. When Canadian data are combined into a winter (DJF) correlation between pressure and temperature, the correlation is -0.72. The Siberian region pressure and temperature correlations do not vary as much as in the Canadian region, they vary between -0.45 and -0.69 for all months. A winter (DJF) correlation for the Siberian region is -0.70. These negative correlations are expected, as an inverse relationship between MSLP and 1000 hPa temperatures is confirmed through the data.

4.a.2. Winter (DJF) Data Analysis: seasons of 1979-2007

4.a.2.i. Mean Sea Level Pressure (MSLP)

The highest winter MSLP in the Northern Hemisphere is slightly to the southwest of the Siberian region (Figure 7a), with stronger pressure gradients in the Siberian region (Figure 7b) when compared to the Canadian region (Figure 7c). When the pressures within the Siberian region (Figure 7b) are averaged, the winter MSLP is 1028.8 hPa with a 7.7 hPa range over the 29 year study period (Figure 8a and Table 6). The Canadian region averages a MSLP of 1018.3 hPa, which is 10.5 hPa lower than the Siberian region MSLP. Wintertime pressures in the Canadian region have a smaller standard deviation (1.6), which translates into less variability with a range of 5.6 hPa. Over the last 29 years, the Siberian region has seen a minimal increase of .01 hPa per year while the Canadian region has a decreasing rate of .05 hPa per year (Table 7), although this study does not test the statistical significance of the trends found. Comparing MSLP between both regions is easier when viewing yearly anomalies. In general, there are years when the anomalies for both regions are in phase (having the same sign) yet there are also times when the anomalies are opposite of each other. Anomaly patterns between both regions are difficult to discern, as similar patterns usually only occur a few years in a row (Figure 8b).

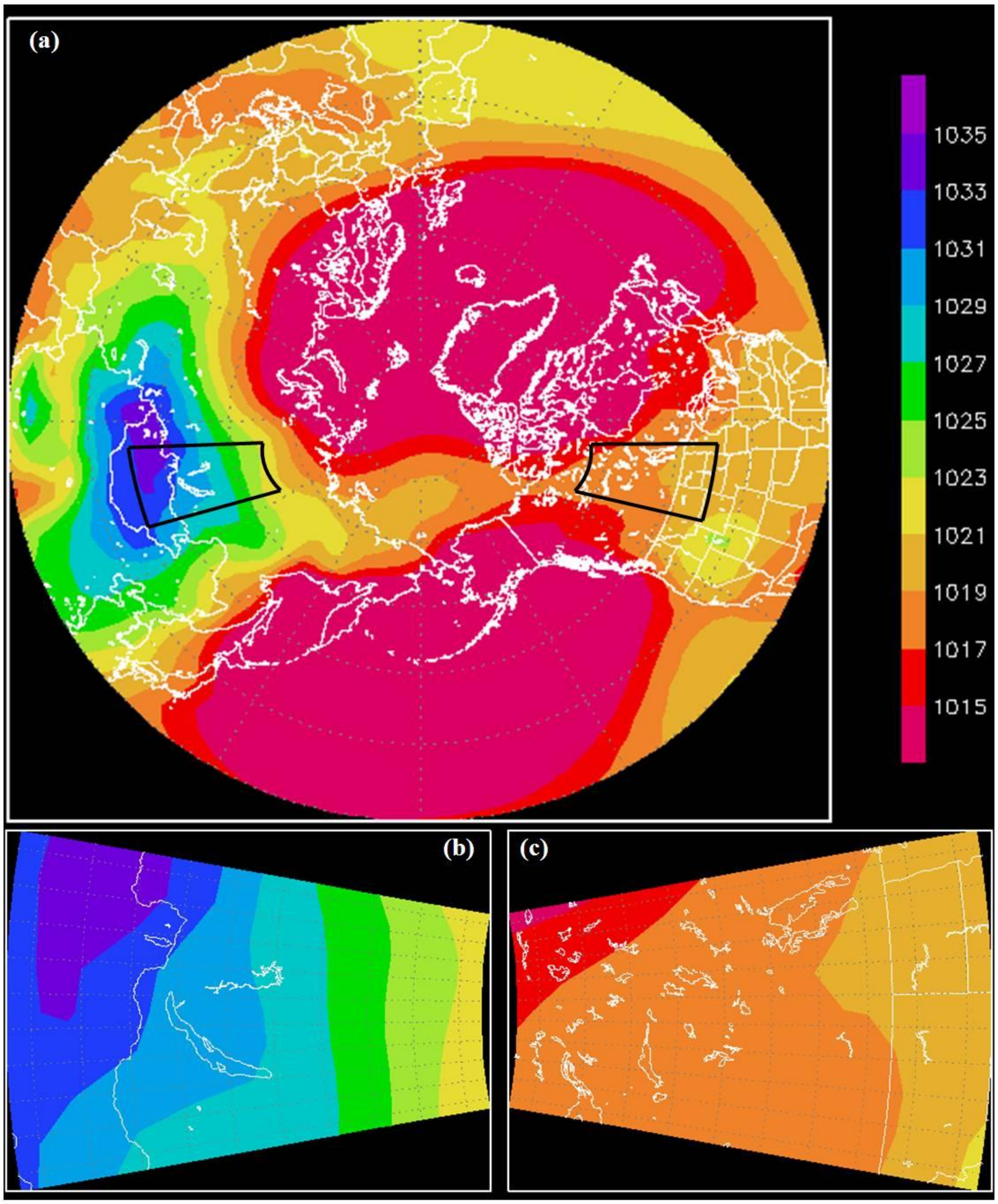
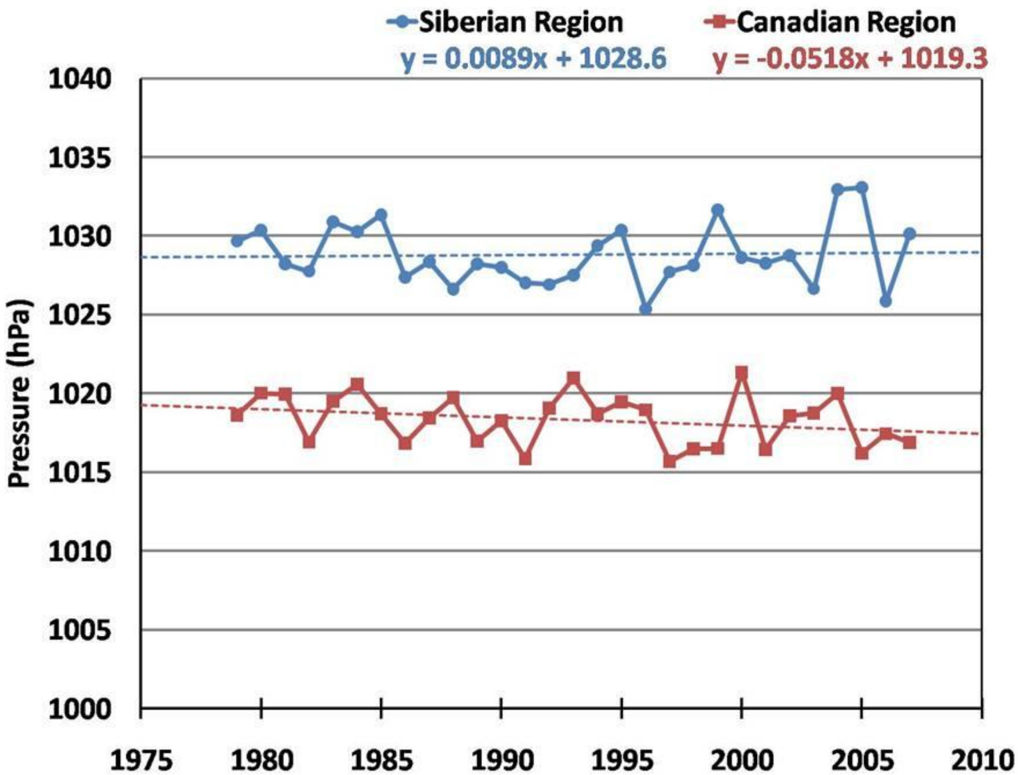


Figure 7: Winter (DJF) 29 year average MSLP in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

(a)



(b)

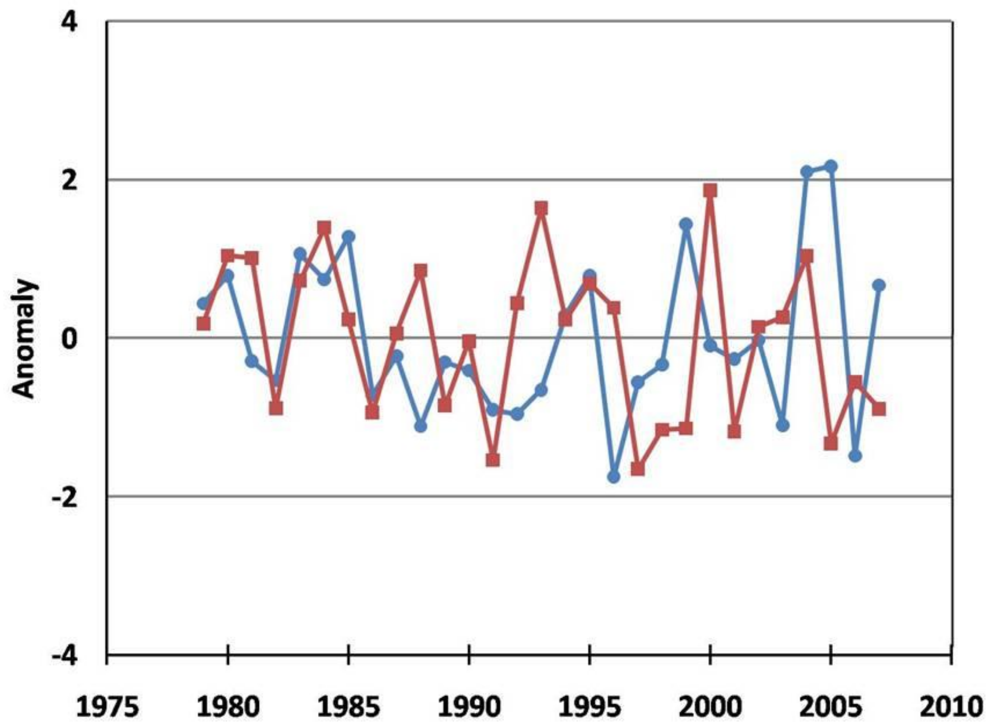


Figure 8: Winter (DJF) (a) MSLP and (b) MSLP anomalies with trend lines plotted for each region.

Table 6: Winter Mean Sea Level Pressure Data Summary (hPa)

	Siberian Region	**Canadian Region**	**Difference**
Mean	1028.8	1018.3	+10.5
Maximum (year)	1033.1 (2005)	1021.3 (2000)	+16.9 (2005)
Minimum (year)	1025.4 (1996)	1015.7 (1997)	+6.4 (1996)
Range	7.7	5.6	10.5
Std. Dev.	2.0	1.6	2.4

Table 7: Trends in MSLP (hPa/year) and 1000 hPa Temperature (°C/year)

Month	**Variable**	**Siberian Region**	**Canadian Region**
October	MSLP	+0.03	-0.04
	Temperature	+0.02	-0.01
November	MSLP	+0.01	-0.03
	Temperature	+0.02	+0.04
December	MSLP	+0.14	-0.09
	Temperature	-0.03	+0.04
January	MSLP	+0.01	-0.05
	Temperature	+0.03	+0.04
February	MSLP	-0.11	-0.02
	Temperature	+0.10	+0.04
March	MSLP	-0.09	+0.05
	Temperature	+0.11	+0.04
Winter	MSLP	+0.01	-0.05
	Temperature	+0.03	+0.06

4.a.2.ii. 1000 hPa Temperature

Northern Hemisphere winter 1000 hPa temperatures are coldest at the North Pole (Figure 9a), and although the larger pressure gradient is present in the Siberian region (Figure 7b and c), the Canadian region has a larger temperature gradient of the two regions (Figure 9b and c). Since no single December, January, or February averaged regional temperatures are above freezing, the average winter temperatures for both regions are also below freezing. Winters in Siberia have average 1000 hPa temperatures of -12.8 °C while Canada is -10.0 °C, 2.8 °C warmer (Figure 10a and Table 8). Winter temperatures are slightly increasing in both regions over the study period, by 0.03 °C per year in the Siberian region and 0.06 °C per year in the Canadian region (Table 7). The coldest winter in the Canadian region occurred in 1981 (-14.3 °C) and temperatures in the Canadian region this year are 2.0 °C colder than the Siberian region. In fact, there are five years in which the Canadian region had colder temperatures than the Siberian region. Temperatures in the Siberian region are as low as -17.1 in the 1984 winter. The range and standard deviation of wintertime temperatures are greater in the Canadian region than in the Siberian region, even though the maximum and minimum temperatures are colder for the Siberian region. Temperature anomalies for both regions generally have similar behaviors from 1989 onward, yet there are a few years when opposite anomalies occur between regions (Figure 10b). Before 1989, opposite temperature anomalies between regions are more than twice as common as after 1989.

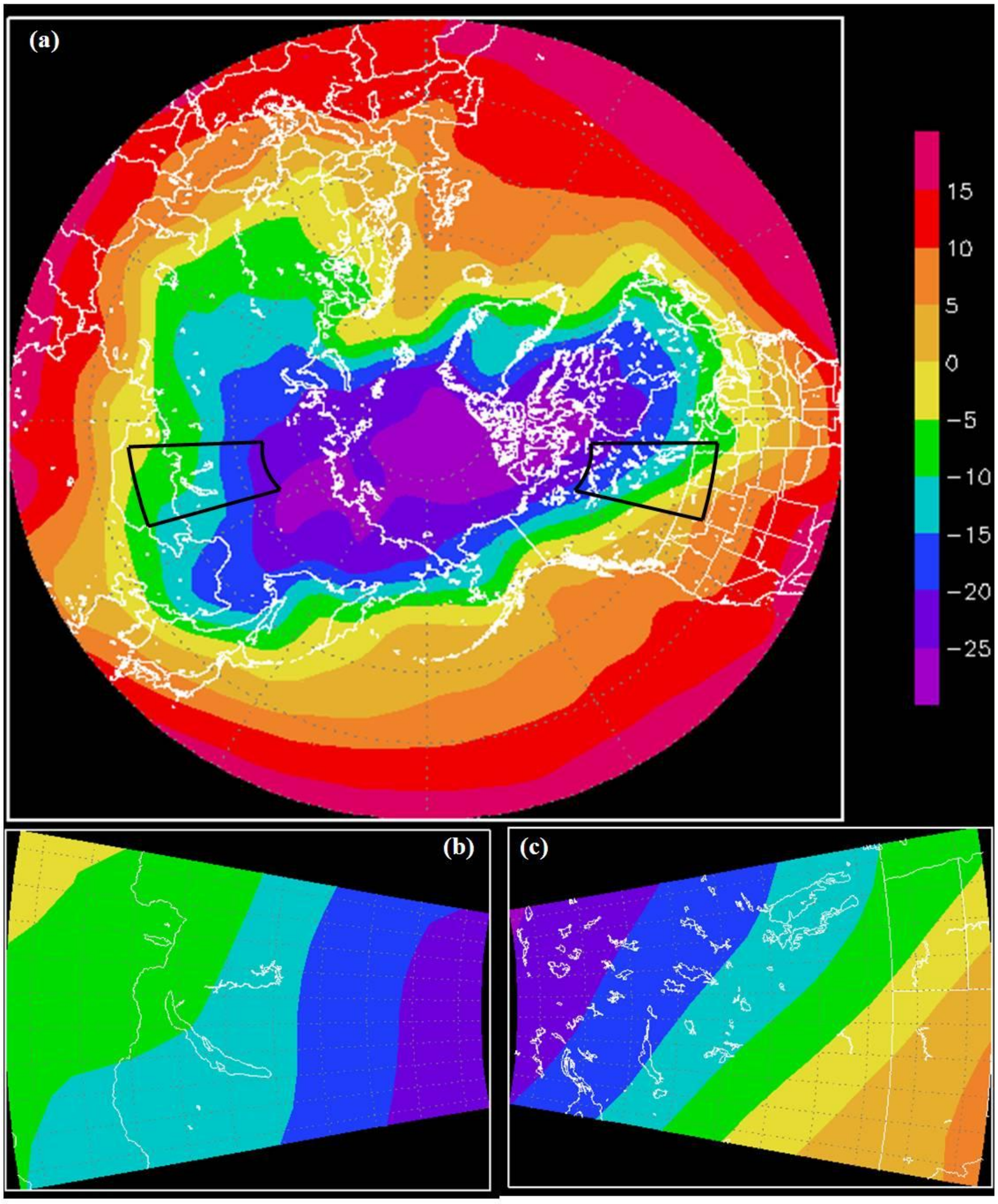


Figure 9: Winter (DJF) 29 year average 1000 hPa temperature in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

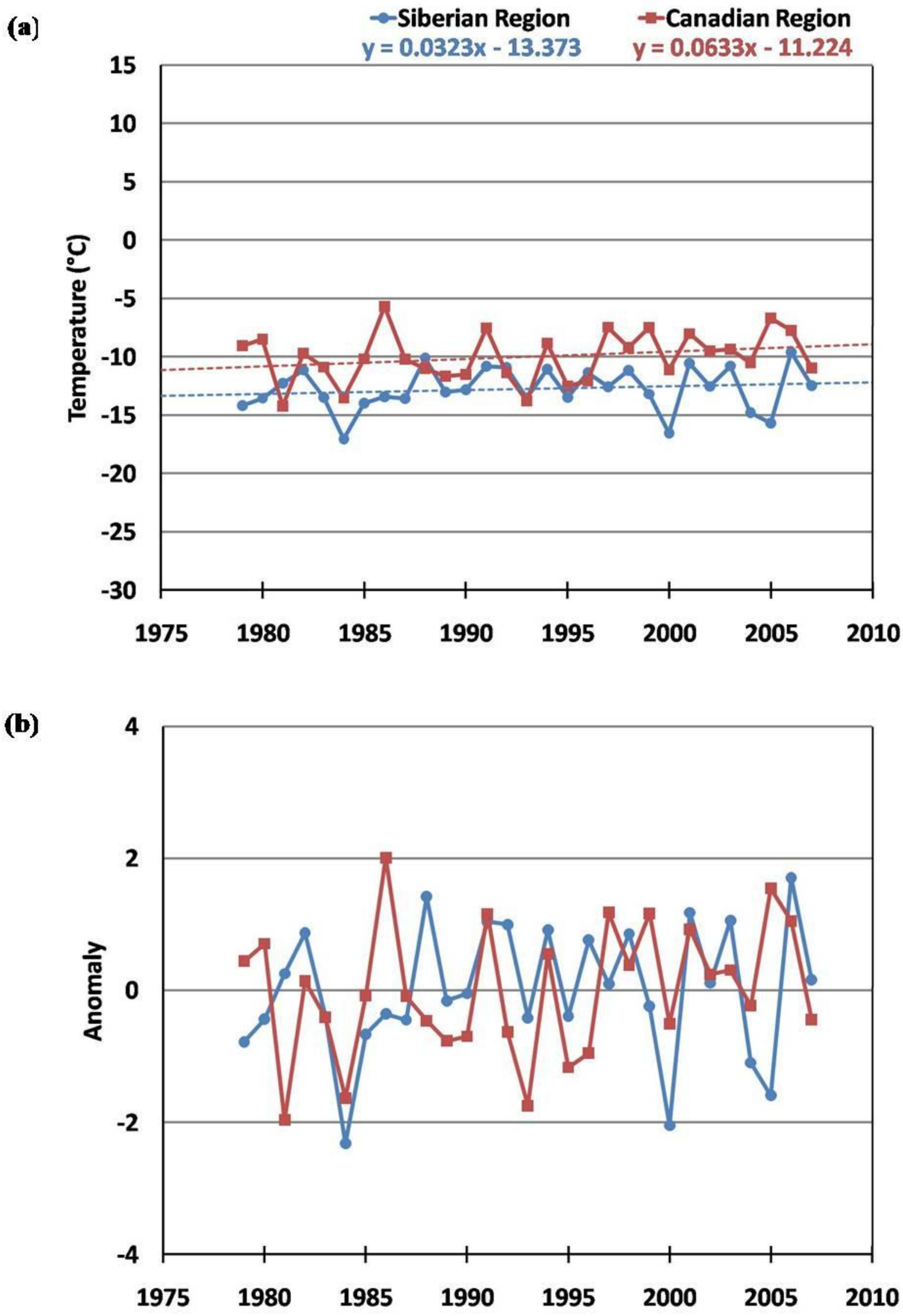


Figure 10: Winter (DJF) (a) 1000 hPa temperature and (b) 1000 hPa temperature anomalies with trend lines plotted for each region.

Table 8: Winter 1000 hPa Temperature Data Summary (°C)

	Siberian Region	Canadian Region	Difference
Mean	-12.8	-10.0	-2.8
Maximum (year)	-9.6 (2006)	-5.7 (1986)	- 9.0 (2005)
Minimum (year)	-17.1 (1984)	-14.2 (1981)	+ 2.0 (1981)
Range	7.5	8.5	11.0
Std. Dev.	1.8	2.2	2.5

4.a.2.iii. Summary

The increasing MSLP trend for the Siberian region found by this study disagrees with the results of Panagiotopoulos et al. (2005), who found a decrease of 2.5 hPa per decade from 1978-2001. Panagiotopoulos et al. (2005) used multiple datasets with varying spatial resolution and incomplete station data from 1920-2001 for analysis over an area 5 ° larger in latitude and 20 ° larger in longitude than this study. These variations could account for different trends found by this study.

Overall, both regions are not experiencing the same trends in winter MSLP and temperature. Pressure and temperature are both increasing within the Siberian region, although by small values (Table 7). These trends could show a shift toward high pressures dominated by dynamic forcings in the Siberian region. The trends in the Canadian region are more expected, decreasing pressures and increasing temperatures, which could be caused by an increased thermodynamic forcing of high pressures in that region. The magnitude of the Canadian region trends are over twice of those in the Siberian region. In 2005, the Siberian region temperatures are 9.0 °C colder than the Canadian region. This extreme difference could have been caused by the largest MSLP difference seen during this study (16.9 hPa) in the same year, as well as the strongest winter MSLP in the Siberian region (1033.1 hPa).

Anomalously high pressure values in either region are usually accompanied by lower than average 1000 hPa temperatures. The magnitudes of the anomalies are not the exact same, as many things can influence temperature besides MSLP. Another expected anomaly situation is to have lower than normal MSLP accompanied by higher than normal temperatures. Both of these cases are most likely subject to thermodynamic processes. However, pressure and temperature do not always have anomalies of opposite sign. Interesting situations occur when there are positive anomalies for both temperature and pressure, or when temperature and pressure are lower than usual. In those situations, synoptic patterns might be more dynamic than thermodynamic in character.

Most common is a situation when both regions have opposite anomalies of pressure and temperature, easily seen in 1984, 1991, 1995, and 2004 (Figure 11). From 1979-2007, there are few instances when pressure and temperature anomalies are the same sign for both regions. For example, during the winter of 1989, both regions have negative anomalies in pressure and temperature (Figure 11), and both regions have positive anomalies in 1994. If there was an even wavenumber of Rossby waves across the hemisphere, this pattern could affect both regions similarly due to the symmetric pressure pattern across the Arctic. Pressure and temperature are higher than normal in the Siberian region and lower than normal in the Canadian region in 2007. As opposed to 1994, the Rossby wavenumber may have been odd in 2007, which resulted in such different anomaly patterns for both regions. Describing anomaly patterns is one of the focuses of this study, although investigating the cause of these conditions is outside the scope of this study.

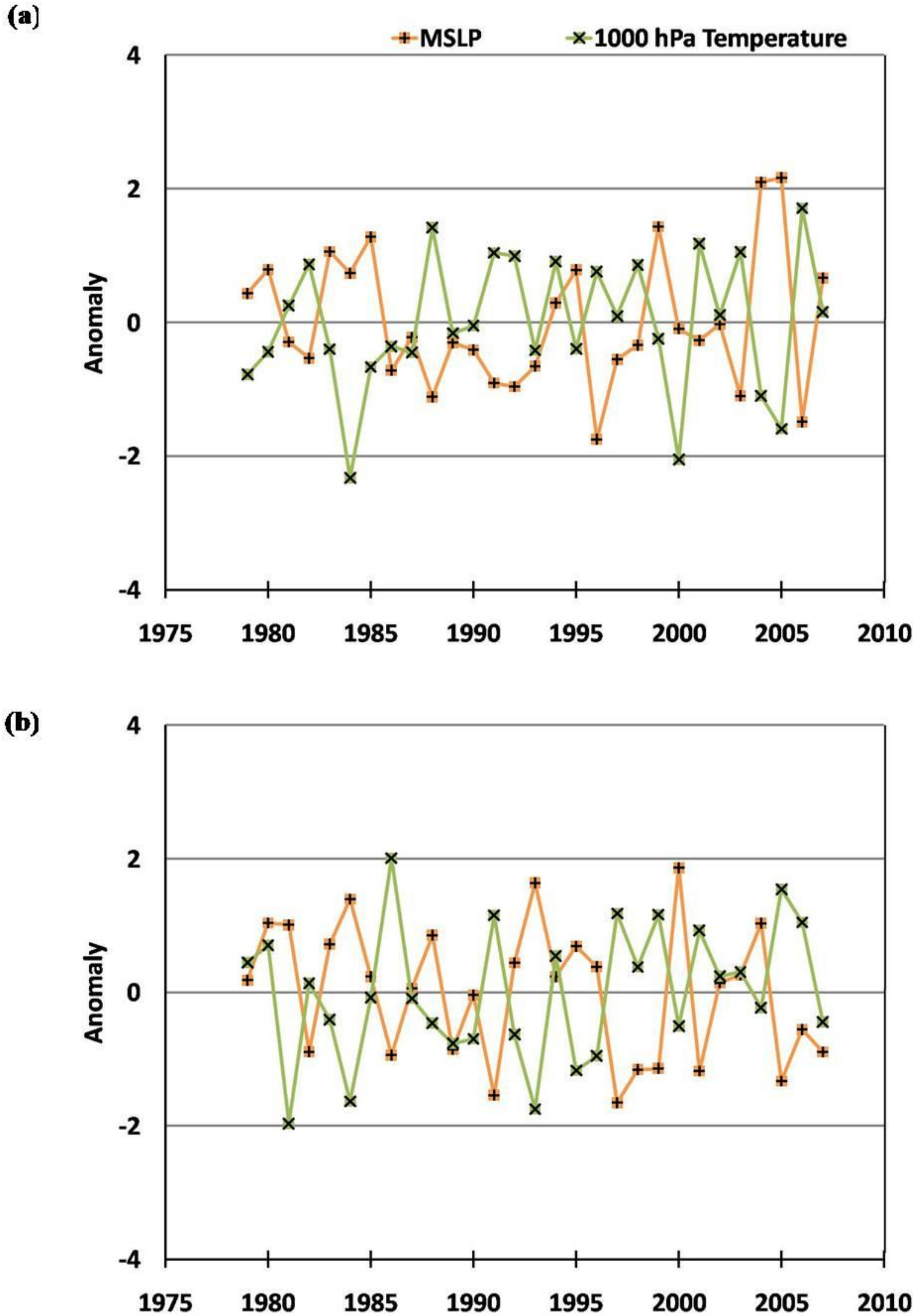


Figure 11: Winter (DJF) MSLP and 1000 hPa temperature anomalies plotted for the (a) Siberian region and (b) Canadian region.

4.a.3. October Data Analysis: 1979-2007

4.a.3.i. Mean Sea Level Pressure (MSLP)

Surface high pressures appear in Asia in October (Figure 12a), with the highest pressures in the Siberian region on the western edge (Figure 12b). Most of the Canadian region has little to no pressure gradient present (Figure 12c). The average October MSLP for the Siberian region for the study period, 1979-2007, is 1020.5 hPa, 6.3 hPa higher than the long-term mean of 1014.2 hPa for the Canadian region (Figure 13a and Table 9). The largest annual difference in MSLP between the Siberian region and Canadian region occurred in 1994 (12.0 hPa), with the smallest difference in 1998 with the Siberian region only 1.5 hPa higher than the Canadian region. Since the Siberian region and Canadian region do not have the same MSLP values, it is easier to compare their behavior by looking at yearly anomaly values (Figure 13b). Overall, there are times when anomalies for both regions are in phase (both having the same sign), however there are also times when the anomalies have the opposite sign and are out of phase between regions. These patterns can occur several seasons in a row although there is no distinct pattern, so discerning a relationship between regions is difficult to do.

4.a.3.ii. 1000 hPa Temperature

Temperatures below freezing exist near the Arctic Circle (Figure 14a), and both study regions have similar temperature patterns in October (Figure 14b and c). The average October 1000 hPa temperature for the Siberian region is 3.8 °C and the Canadian region is 6.1 °C, 2.3 °C warmer (Figure 13c and Table 9). In 2000, the largest

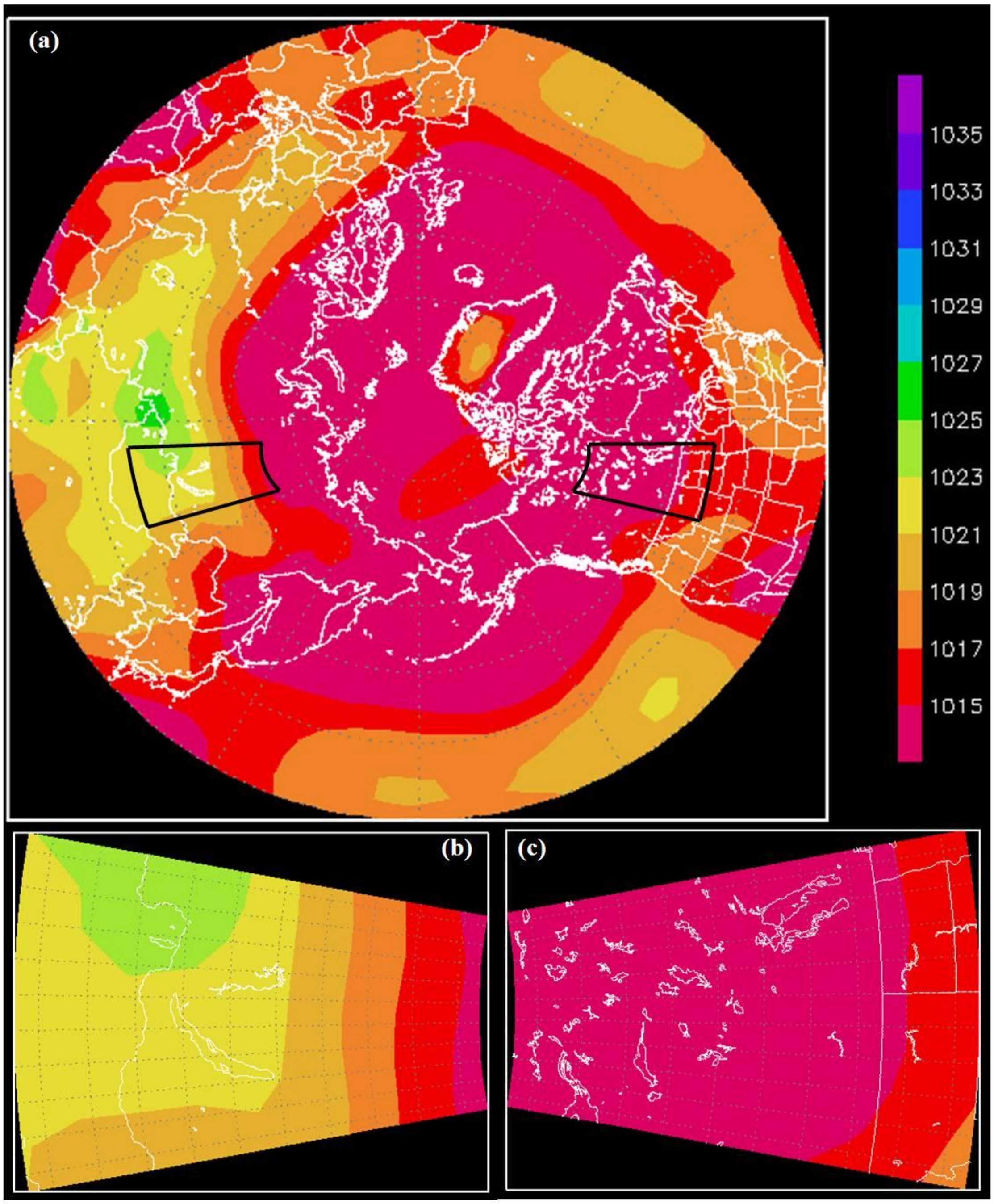


Figure 12: October 29 year average MSLP in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

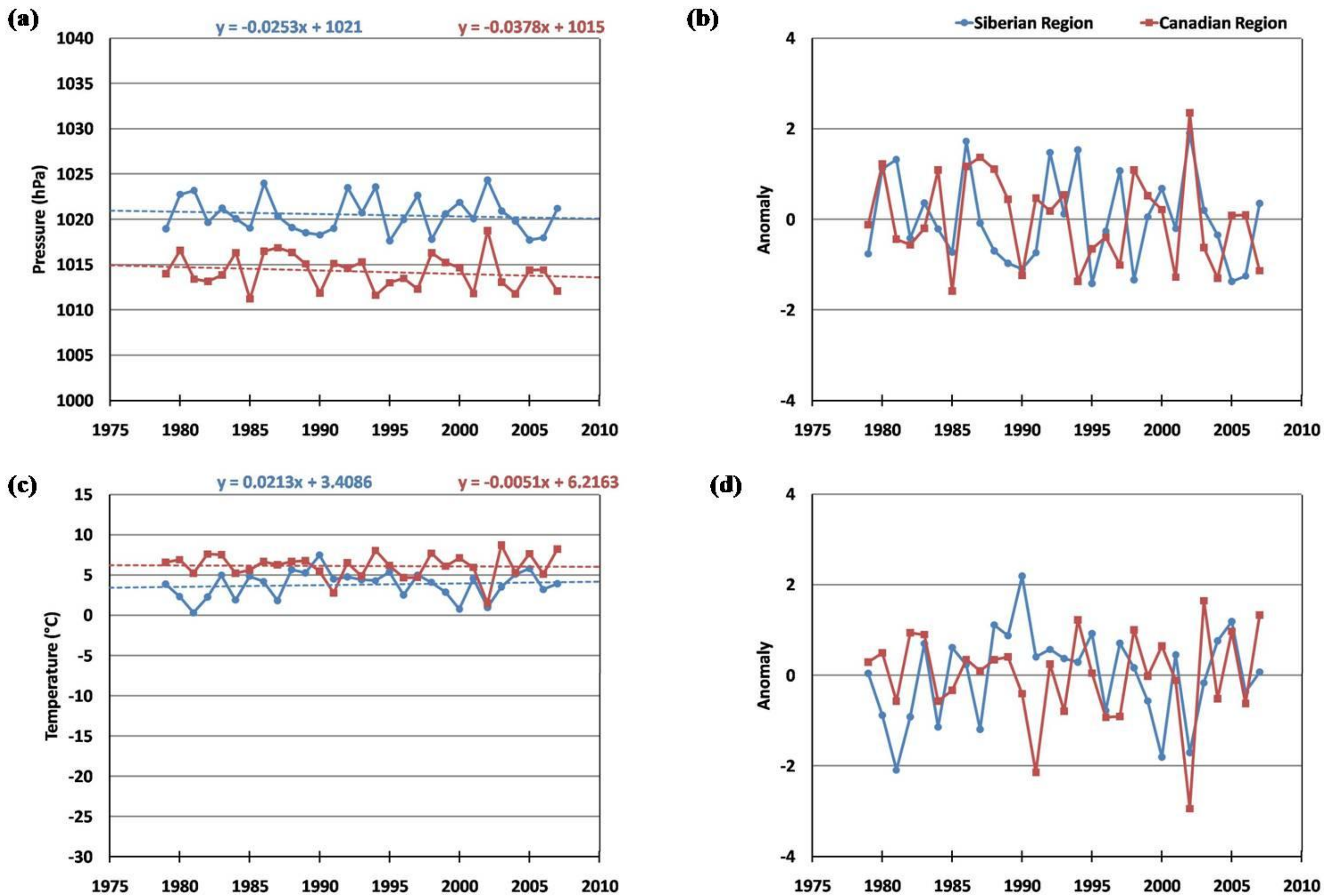


Figure 13: October reanalysis data for (a) MSLP, (b) MSLP anomalies, (c) 1000 hPa temperature , and (d) 1000 hPa temperature anomalies with trend lines plotted for each region.

Table 9: October Data Summary

	Siberian Region		Canadian Region		Difference	
	MSLP (hPa)	1000 hPa Temp (°C)	MSLP (hPa)	1000 hPa Temp (°C)	MSLP (hPa)	1000 hPa Temp (°C)
Mean	1020.5	3.8	1014.2	6.1	+6.3	-2.3
Maximum (year)	1024.3 (2002)	7.5 (1990)	1018.7 (2002)	8.7 (2003)	+12.0 (1994)	+2.0 (1990)
Minimum (year)	1017.6 (1995)	0.3 (1981)	1011.2 (1982)	1.5 (2002)	+1.5 (1998)	-6.3 (2000)
Range	6.7	7.2	7.5	7.2	10.5	8.3
Std. Dev.	2.0	1.7	1.9	1.6	2.5	2.1

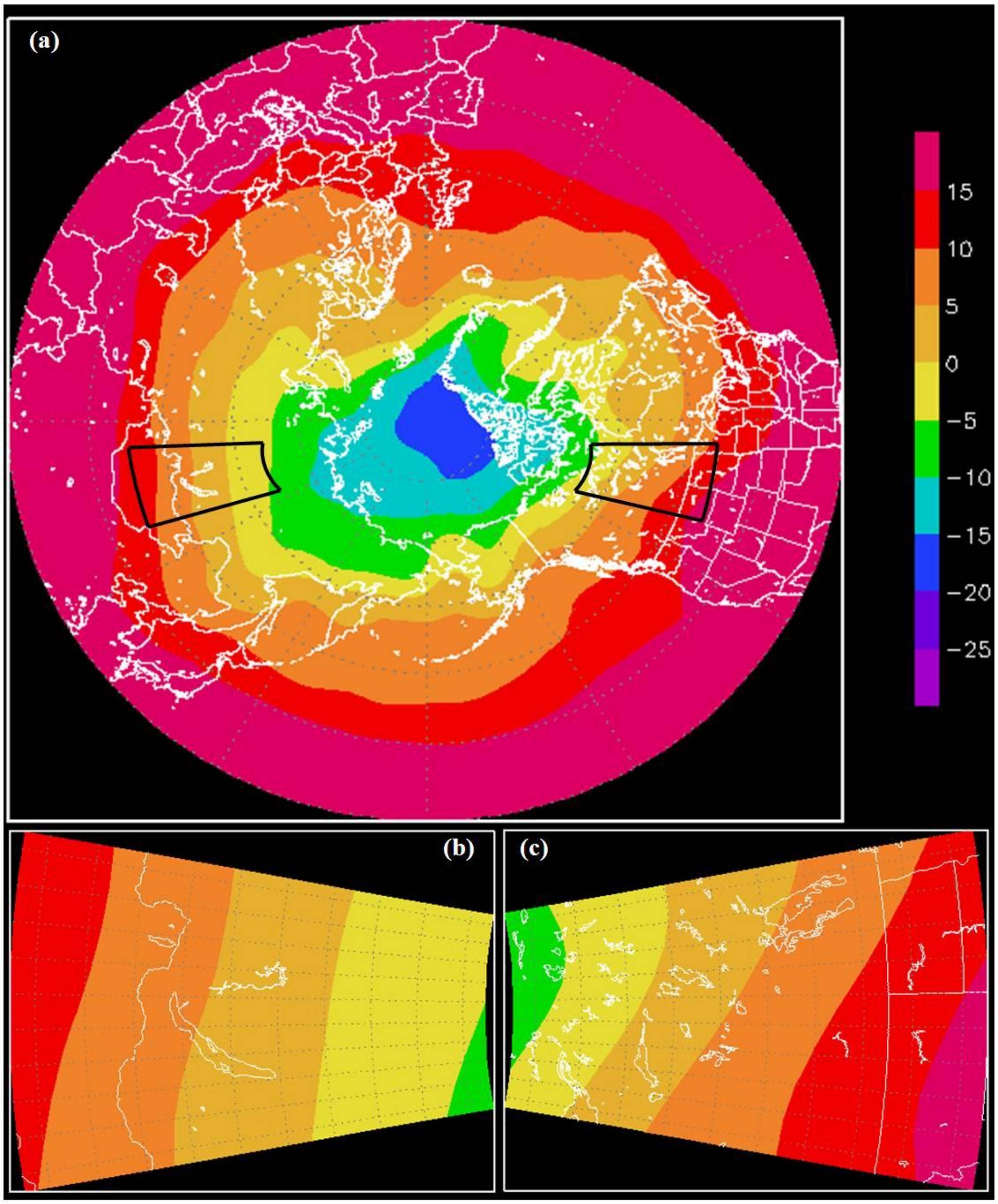


Figure 14: October 29 year average 1000 hPa temperature in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

temperature difference between the two regions occurs when the Siberian region is colder by 6.4 °C. At most, temperatures in the Canadian region are colder than the Siberian region by 2.0 °C in 1991. 1990, 1991, and 1997 are the only years for this study period when temperatures are colder in the Canadian region than the Siberian region. There are times when temperature anomalies for both regions increase or decrease at the same time (1979-1988 and 1995-2007), yet, there are also times when they move in opposite directions (1988-1994) (Figure 13d). However, the time intervals of the temperature anomaly patterns do not exactly match with patterns in the regions' MSLP anomalies.

4.a.3.iii. Summary

There are no trends greater than 1.5 hPa or 1.5 °C over the 29 years in MLSP or 1000 hPa temperature for either region in October (Table 7). However, small trends for both variables are increasing in the Siberian region yet decreasing in the Canadian region. A cause for this could be the earlier development of high pressures in the Siberian region than in the Canadian region.

The MSLP in 2002 are the strongest individual October pressure values for both study regions, 1024.3 hPa for the Siberian region, and 1018.7 hPa in the Canadian region (Table 9). The coldest Canadian region 1000 hPa temperature, 1.5 °C, in this study period is also in October 2002. October 2002 is unusually cold for the Siberian region as well (0.9 °C), and only 0.6 °C away from being the coldest October month. The Arctic Oscillation value for this month is the lowest for any October in this study period

(NOAA/NWS/CPC 2010). The negative phase of the Arctic Oscillation has been shown to be a main factor influencing the atypically high MSLP and low 1000 hPa temperatures for both regions (Cohen and Entekhabi 1999). Justifying pressure and temperature anomalies through the Arctic Oscillation happens as expected in this situation, although it remains to be seen if the Arctic Oscillation can always be used to account for pressure and temperature anomalies and is not a main focus this study.

4.a.4. November Data Analysis: 1979-2007

4.a.4.i. Mean Sea Level Pressure (MSLP)

Most of central Asia is under the influence of high pressure in November (Figure 15a). MSLP are increasing from the south in both regions (Figure 15b and c). The November average MSLP for the Siberian region is 1025.0 hPa, 9.0 hPa higher than the average of 1016.0 hPa for the Canadian region (Figure 16a and Table 10). While neither region is experiencing a large trend in MSLP, pressures are minimally increasing in the Siberian region yet decreasing in the Canadian region (Table 7). In 1980, the Siberian region has its lowest November MSLP value (1018.4 hPa). The next year, the Siberian region MSLP increases dramatically to 1031.4 hPa, the strongest November value in this study. Unfortunately, this quick turnaround is hard to explain using the phase of the Arctic Oscillation, as November 1980 and 1981 are both negative phases (NOAA/NWS/CPC 2010). 1981 is also the year of greatest MSLP difference between both locations, with the Siberian region MSLP 17 hPa stronger than the Canadian region MSLP. The smallest difference between the Siberian region and the Canadian region is

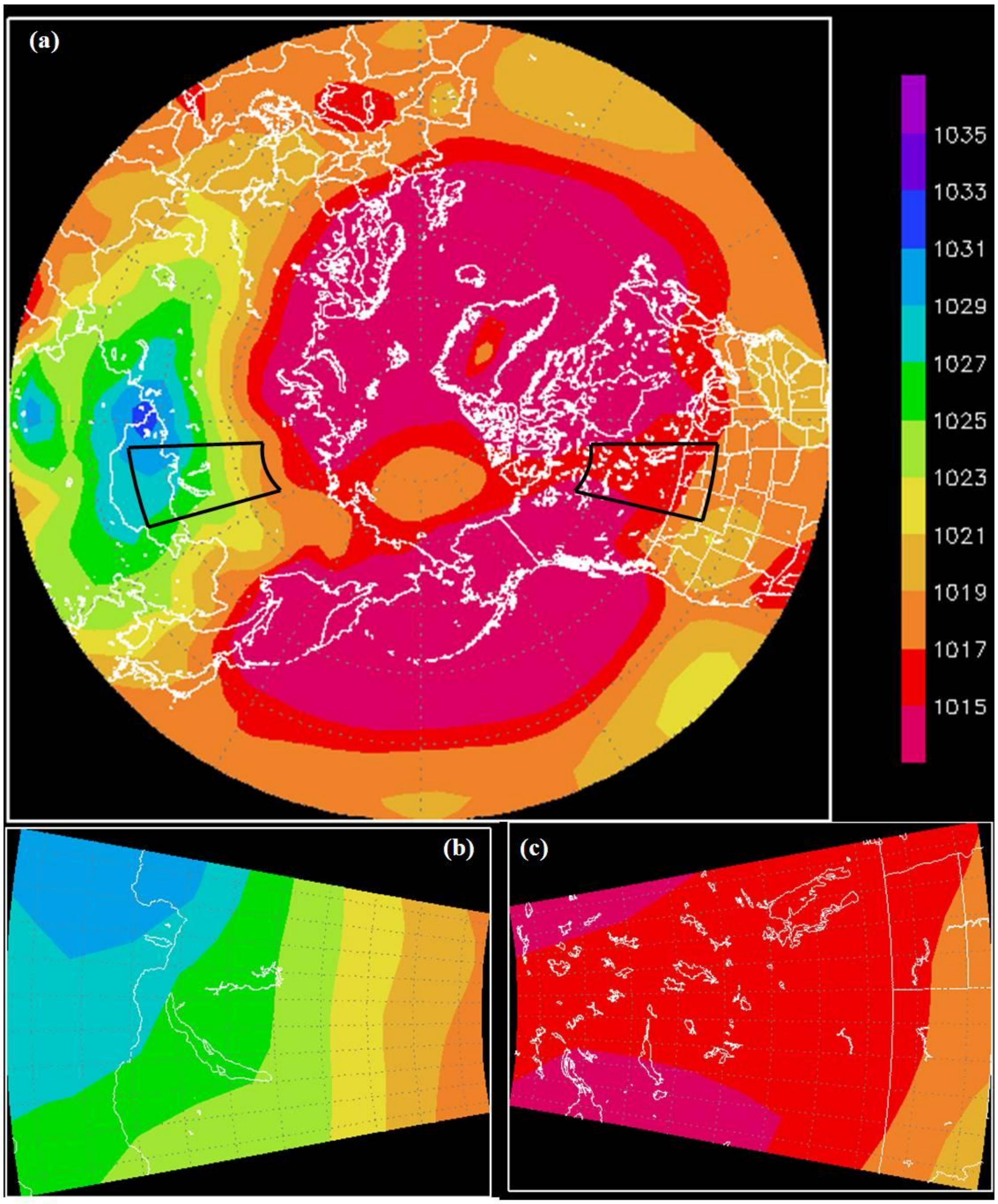


Figure 15: November 29 year average MSLP in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

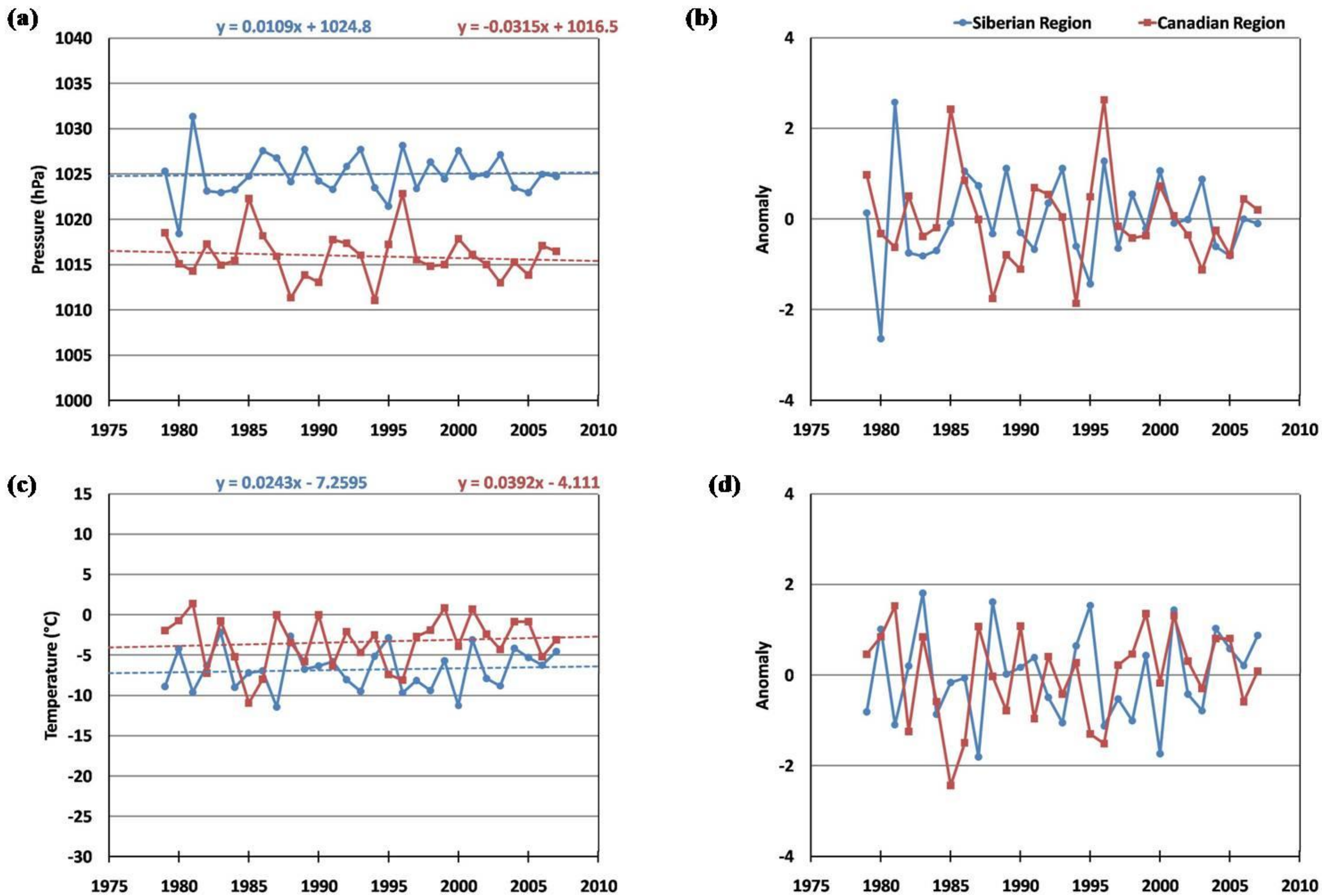


Figure 16: November reanalysis data for (a) MSLP, (b) MSLP anomalies, (c) 1000 hPa temperature , and (d) 1000 hPa temperature anomalies with trend lines plotted for each region.

Table 10: November Data Summary

	Siberian Region		Canadian Region		Difference	
	MSLP (hPa)	**1000 hPa Temp (°C)**	**MSLP (hPa)**	**1000 hPa Temp (°C)**	**MSLP (hPa)**	**1000 hPa Temp (°C)**
Mean	1025.0	-6.8	1016.0	-3.4	+9.0	-3.4
Maximum (year)	1031.4 (1981)	-2.1 (1983)	1022.8 (1996)	1.4 (1981)	+17.0 (1981)	+4.6 (1995)
Minimum (year)	1018.4 (1980)	-11.4 (1987)	1011.1 (1994)	-11.0 (1985)	+2.5 (1985)	-11.4 (1987)
Range	13.0	9.3	11.7	12.4	14.5	16.0
Std. Dev.	2.5	2.6	2.6	3.1	3.3	3.9

2.5 hPa in 1985, which is also a negative phase for the Arctic Oscillation. Variability in MSLP for both regions in November increases 20-30% with respect to October MSLP (Tables 9 and 10). The largest November MSLP anomalies for both regions occur prior to 1997 (Figure 16b).

4.a.4.ii. 1000 hPa Temperature

Cold temperatures from the Arctic Ocean continue to expand southward (Figure 17a), and November is the first month when monthly average temperature values are below freezing for both regions (Table 7). The temperature gradients within each region are similar to each other (Figure 17b and c). Every November monthly temperature in the Siberian region is below freezing, while five months are at or above freezing in the Canadian region from the study period. The mean November 1000 hPa temperature for the Siberian region is -6.8 °C and -3.4 °C for the Canadian region (Figure 16c and Table 10), and temperatures in both regions have minimally increased throughout the study period (Table 7). The largest difference between the Siberian region and Canadian region 1000 hPa temperatures in November is 11.4 °C in 1987, with the Siberian region being the colder of the two. The Canadian region is colder than the Siberian region in six out of the 29 years: 1982, 1985, 1986, 1988, 1991, and 1995. At most, the Canadian region is 4.6 °C colder than the Siberian region (1995). Temperature variability in the Siberian region increases by 50% from October to November, and temperature variability almost doubles for the Canadian region (Tables 9 and 10). Temperature anomalies between the two regions do not appear to have a common pattern

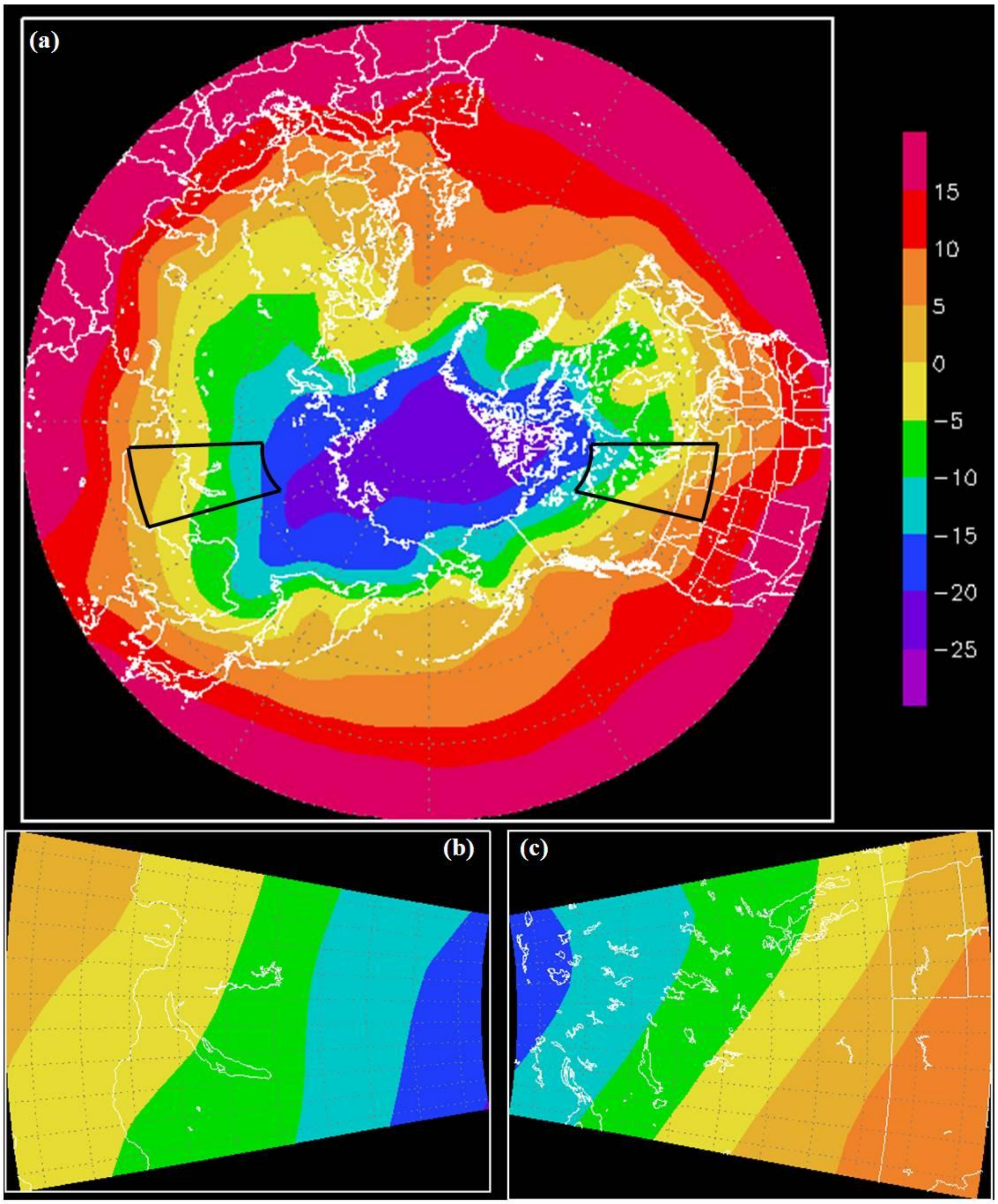


Figure 17: November 29 year average 1000 hPa temperature in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

or relationship, they are in phase 18 years and out of phase 11 years of the 29 years studied (Figure 16d).

4.a.4.iii. Summary

The greatest pressure range for the 29 years in the Siberian region occurs from 1980 to 1981, when pressure increases 13.0 hPa from 1018.4 hPa to 1031.4 hPa (Table 10). This large pressure change does not produce the largest year-to-year temperature change, although the temperature anomaly is negative as expected (Figure 16b and d). This difference can be explained by the southward [northward] shift in the high pressure synoptic pattern over Siberia in 1980 [1981] (NOAA/OAR/ESRL PSD 2009). With such a large anomaly shift in the Siberian region, there is almost no anomaly difference from 1980 to 1981 for the Canadian region. However, a large anomaly change in the Canadian region occurs the following year, from 1981 to 1982. In 1981, the Canadian region temperature is 1.4 °C, 11 °C warmer than the temperature in the Siberian region, -9.6°C (Figure 16c and Table 10). The next year, 1982, there is a 12 °C temperature shift and temperatures in the Siberian region are 1 °C warmer than temperatures in the Canadian region due to the warmest November temperature in the Siberian region occurring that year (-2.1 °C). MSLP anomalies also switch between the regions from 1981 to 1982 when Siberian MSLP anomalies change from positive to negative and Canadian MSLP anomalies change from negative to positive (Figure 16b). This turnaround could be explained by the Arctic Oscillation's phase change from negative in 1981 to positive in 1982 (NOAA/NWS/CPC 2010).

While November 1985 has normal pressure and temperature anomalies in the Siberian region, strong anomalies are present in the Canadian region (Figure 16b and d). These strong anomalies in the Canadian region result in the coldest November temperature and second highest MLSP anomaly of this study. There must have been an enhanced synoptic weather pattern over the Canadian region for this to be the only region affected during November 1985, perhaps influenced by a change in the planetary Rossby wave pattern. Similar anomalies occur for both the Canadian region and Siberian region in 1996, when both regions have positive MSLP anomalies and negative temperature anomalies. The planetary waves present during this time may have been even in number, creating a balanced or symmetric weather pattern around the Northern Hemisphere, which is why both locations experienced similar anomalies.

4.a.5. December Data Analysis: 1979-2007

4.a.5.i. Mean Sea Level Pressure (MSLP)

By December, the center of high pressure continues to strengthen over Asia, a small area of weak high pressure starts to form in the United States (Figure 18a), with pressure gradients increasing in both regions (Figure 18b and c). The average December MSLP for the Siberian region is 1028.4 hPa, 11.0 hPa higher than the average of 1017.4 hPa for the Canadian region (Figure 19a and Table 11). For December, the Siberian region MSLP has increased by 0.14 hPa per year for the study, while the Canadian region MSLP has decreased by 0.09 hPa per year for the same period (Table 7). Overall, pressure variability for both regions are similar (Table 11), 20-40% greater than in November (Table 10) and 70% greater than in October (Table 9). Prior to 1989,

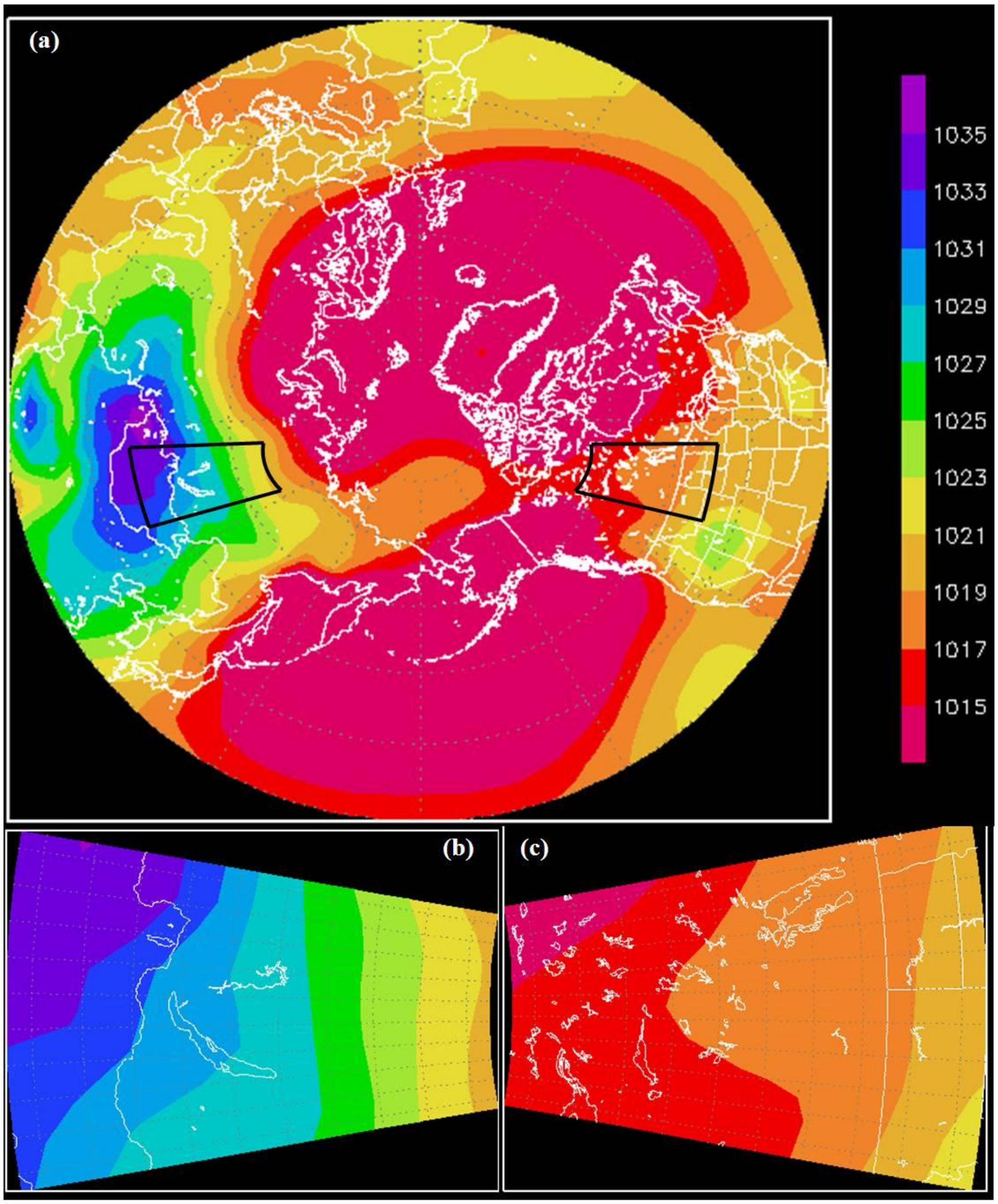


Figure 18: December 29 year average MSLP in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

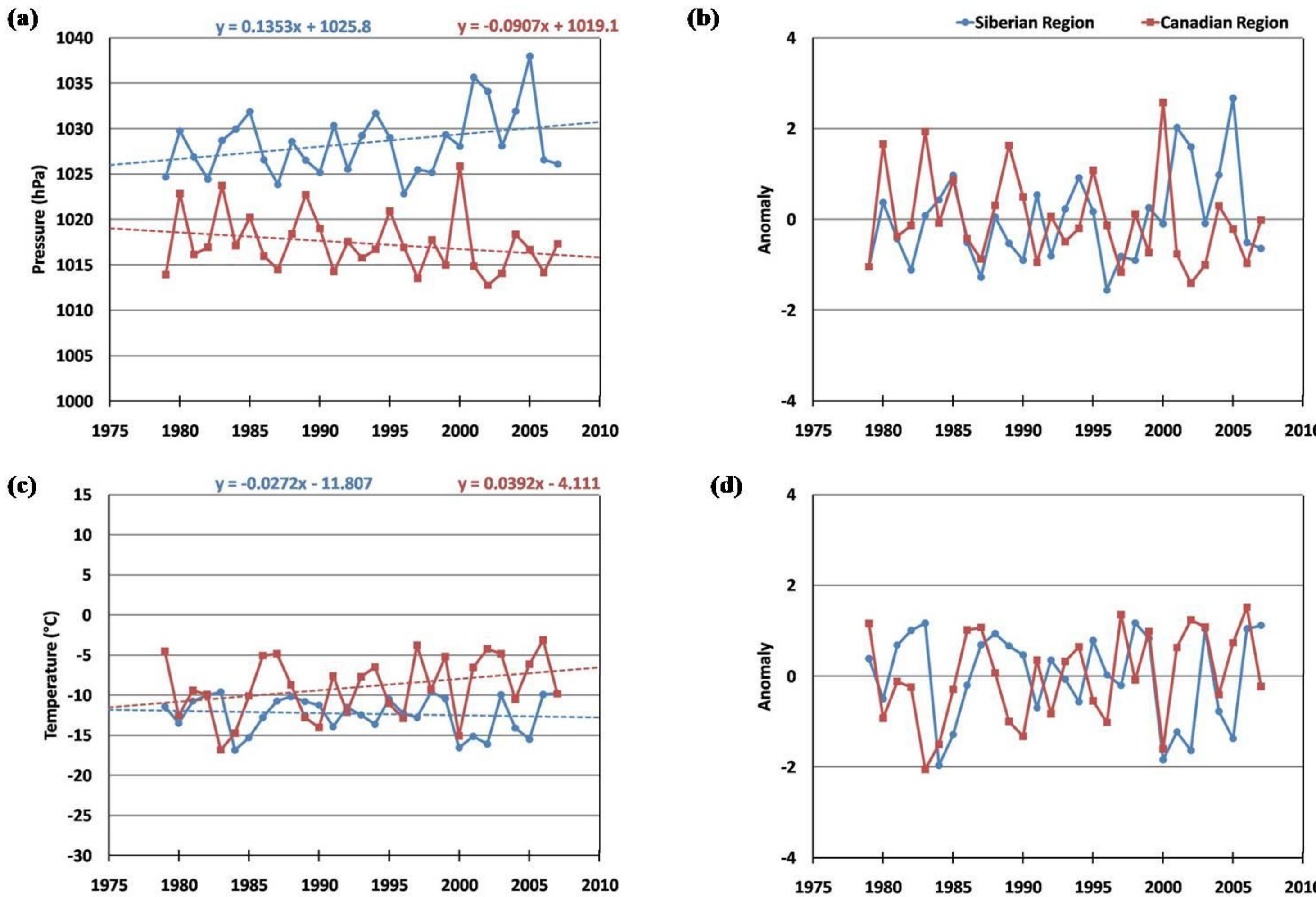


Figure 19: December reanalysis data for (a) MSLP, (b) MSLP anomalies, (c) 1000 hPa temperature , and (d) 1000 hPa temperature anomalies with trend lines plotted for each region.

Table 11: December Data Summary

	Siberian Region		Canadian Region		Difference	
	MSLP (hPa)	1000 hPa Temp (°C)	MSLP (hPa)	1000 hPa Temp (°C)	MSLP (hPa)	1000 hPa Temp (°C)
Mean	1028.4	-12.3	1017.4	-9.0	+11.0	-3.4
Maximum (year)	1038.0 (2005)	-9.6 (1998)	1025.8 (2000)	-3.2 (2006)	+21.4 (2002)	+7.2 (1983)
Minimum (year)	1022.8 (1996)	-16.9 (1984)	1012.8 (2002)	-16.8 (1983)	+2.2 (2000)	-11.9 (2002)
Range	15.2	7.3	13.0	13.6	19.2	19.1
Std. Dev.	3.6	2.3	3.3	3.8	4.9	4.3

MSLP anomalies in the Siberian and Canadian regions are in phase with each other. Since 1989, the anomalies are out of phase for both regions, with one increasing while the other is decreasing or the reverse (Figure 19b).

4.a.5.ii. 1000 hPa Temperature

December temperatures for both regions are well below freezing every year with temperatures as cold as -25 °C appearing over the Arctic Ocean and northern Siberia (Figure 20a). While similar temperatures occur in both study regions, there is a larger gradient in the Siberian region (Figure 20b and c). The long-term December 1000 hPa temperature for the Siberian region is -12.3 °C and -9.0 °C for the Canadian region (Figure 19c and Table 11). Temperatures in the Canadian region 1000 hPa temperature are increasing at a rate of 0.04 °C per year, and decreasing by 0.03 °C per year in the Siberian region (Table 7). Overall, temperature variability is less in both regions in December than in November (Table 10). December temperatures in the Siberian region are less variable than in the Canadian region, with a standard deviation of 2.30 as compared to 3.83 for the Canadian region (Table 11). With the exception of 1990-1999, when the temperature anomalies behave opposite one another, temperature anomalies between both regions generally are in phase with each other (Figure 19d).

4.a.5.iii. Summary

Anomalies from 2000-2005 went through large changes for both regions, as opposed to the majority of the 1990s, which have smaller pressure and temperature anomalies (Figure 19b and d). MSLP anomalies in the Siberian region from 2000-2005

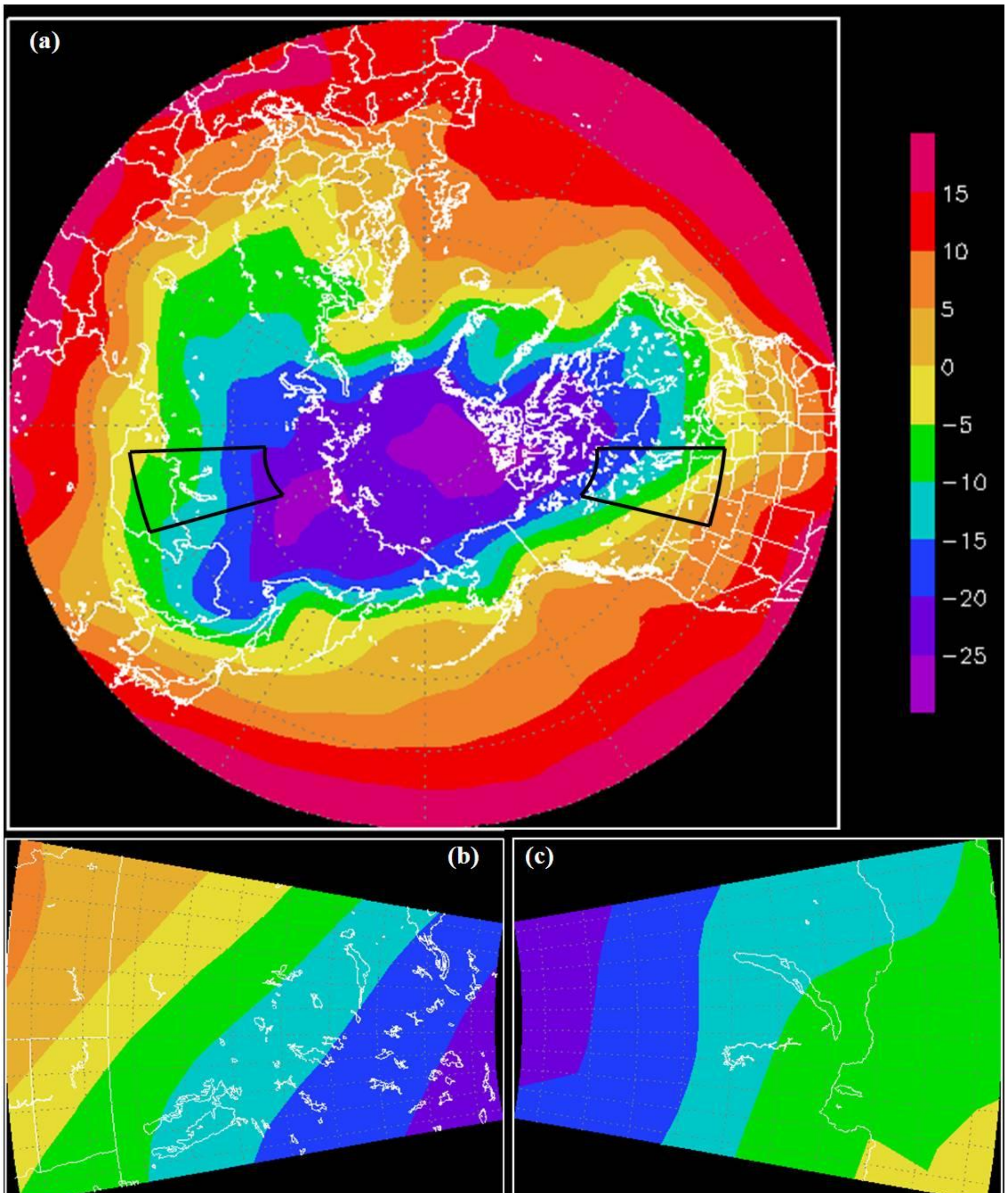


Figure 20: December 29 year average 1000 hPa temperature in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

are much higher than normal, which is also accompanied by some of the most negative temperature anomalies in the study period. The Canadian region, however, has lower than average MLSP during this recent period as well as higher than normal temperatures. These opposite patterns between regions are echoed in opposite MSLP and temperature trends for both regions (Table 7).

During 2002, the year with the largest pressure difference for the two regions, the Siberian region is 11.9 °C colder than the Canadian region, the greatest December temperature difference recorded by this study. The smallest MSLP difference between the Siberian region and Canadian region is 2.2 hPa in 2000, the largest is 21.4 hPa in 2002 (Table 11). There must be a cause for this strong of a change, however, 2000-2002 are all strong negative years for the Arctic Oscillation (NOAA/NWS/CPC 2010). Therefore, using the Arctic Oscillation phase as a foundation for MSLP and 1000 hPa relationships between the two study regions should not be used on its own and is not investigated any further by this study.

4.a.6. January Data Analysis: 1980-2008 (seasons of 1979-2007)

4.a.6.i. Mean Sea Level Pressure (MSLP)

The high pressure system over Asia continues to strengthen in January, and a small ridge is starting to reach over the Arctic Ocean into North America (Figure 21a). The strongest pressure values in the Siberian region are concentrated in the southwestern corner of the region (Figure 21b), while high pressures move into the Canadian region directly from the south (Figure 21c). The MSLP for the Siberian region peaks in strength

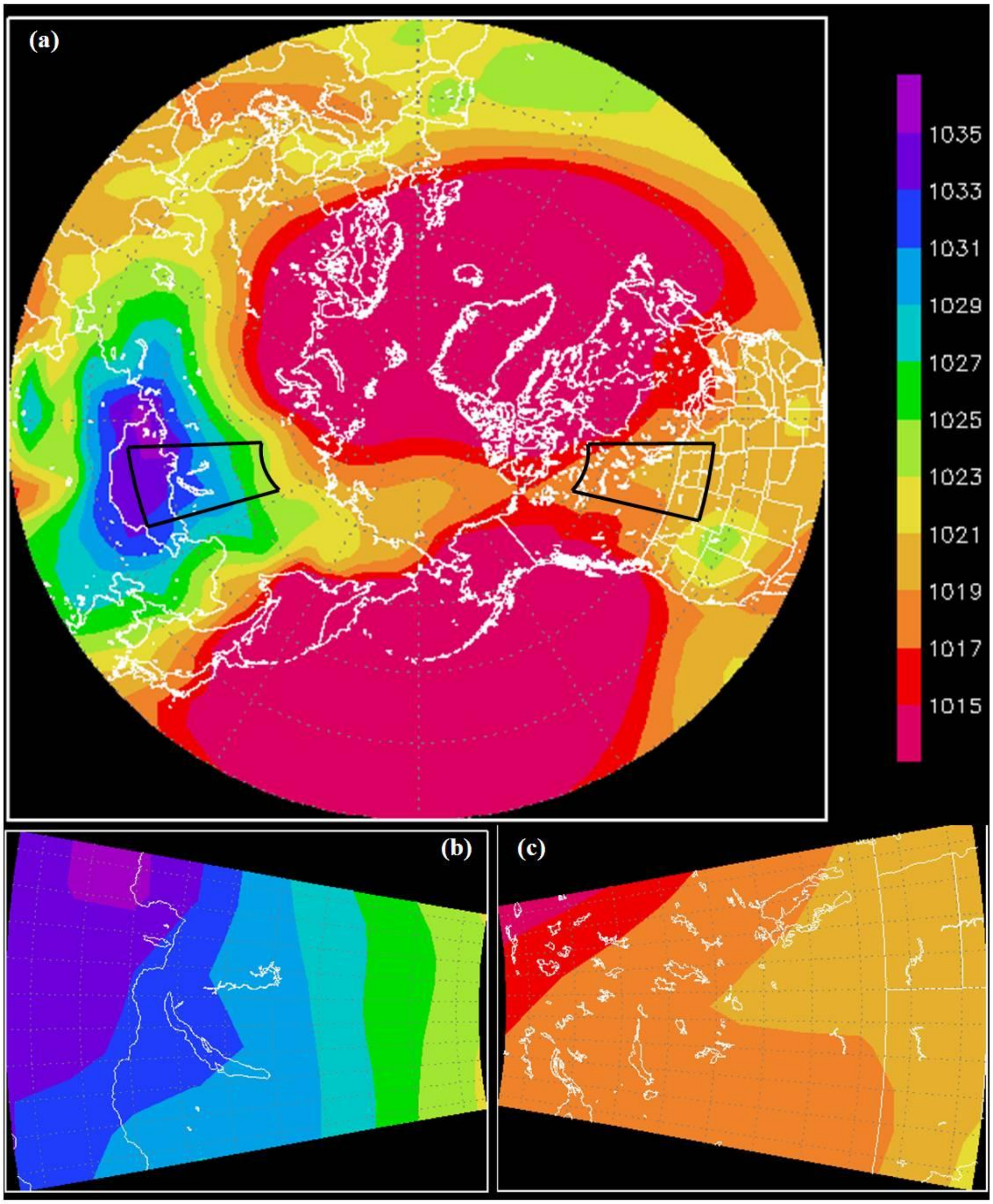


Figure 21: January 29 year average MSLP in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

in January with a 29 year average value of 1030.2 hPa (Figure 22a and Table 12). The average January Canadian region MSLP is 1018.5 hPa, yet January is not the peak winter value. At most, the Siberian region is 20.4 hPa stronger than the Canadian region in 1990 while the smallest MSLP difference is 1.5 hPa in 1994. Overall, the MSLP trend in the Siberian region is steady, while MSLP in the Canadian region is decreasing by .05 hPa per year (Table 7). MSLP anomalies between the Siberian and Canadian regions are similar to each other from 1980-1993 with small anomalies (Figure 22b). Since 1993, MSLP anomalies are larger, more variable, and frequently have opposite signs between regions. From December to January, pressure variability decreases in the Siberian region (Tables 11 and 12). Since January is the peak winter MSLP in the Siberian region, it makes sense that pressure variability decreases. Pressure variability increases in the Canadian region from December to January since MSLP is not yet at its winter peak, which occurs in February.

4.a.6.ii. 1000 hPa Temperature

The coldest temperatures of winter extend past the Arctic basin and into Asia and North America in January (Figure 23a). As opposed to December (Figure 19b and c), the temperature gradient in the Canadian region in January is larger than in the Siberian region (Figure 23b). The Canadian temperature gradient is due to a small area of above freezing temperatures on the southern edge of the region (Figure 23c). The average January 1000 hPa temperature for the Siberian region is -14.6 °C and -11.4 °C for the Canadian region, which is the coldest month of winter for both locations (Figure 22c and Table 12). Temperatures in both regions have a small increasing trend, 0.03 °C per year

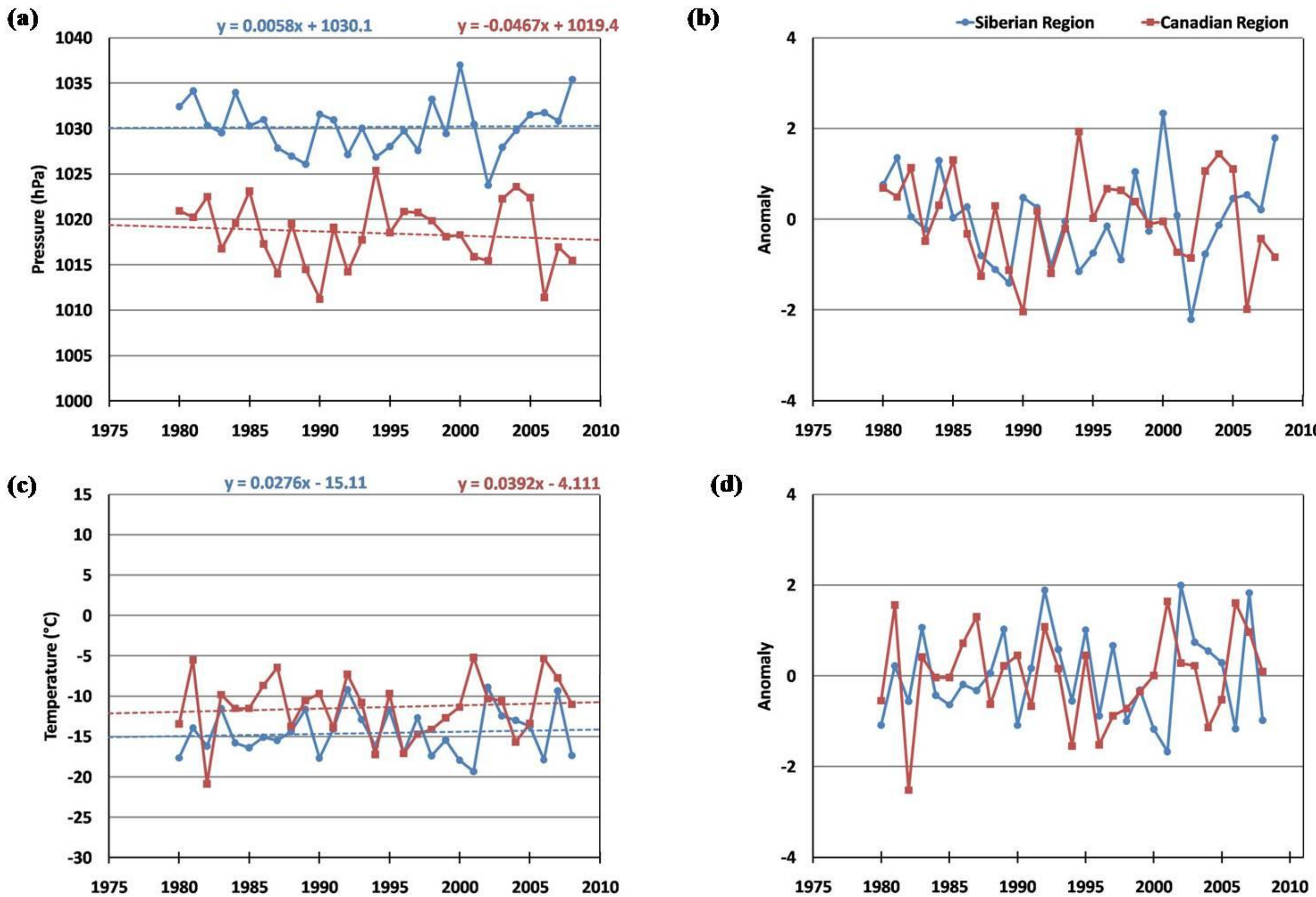


Figure 22: January reanalysis data for (a) MSLP, (b) MSLP anomalies, (c) 1000 hPa temperature , and (d) 1000 hPa temperature anomalies with trend lines plotted for each region.

Table 12: January Data Summary

	Siberian Region		Canadian Region		Difference	
	MSLP (hPa)	**1000 hPa Temp (°C)**	**MSLP (hPa)**	**1000 hPa Temp (°C)**	**MSLP (hPa)**	**1000 hPa Temp (°C)**
Mean	1030.2	-14.6	1018.5	-11.4	+11.7	-3.2
Maximum (year)	1037.0 (2000)	-8.9 (2002)	1025.4 (1994)	-5.2 (2001)	+20.4 (1990)	+4.7 (1982)
Minimum (year)	1023.8 (2002)	-19.3 (2001)	1011.2 (1990)	-20.9 (1982)	+1.5 (1994)	-14.1 (2001)
Range	13.2	10.4	14.2	15.7	18.9	18.8
Std. Dev.	2.9	2.9	3.6	3.8	4.6	4.4

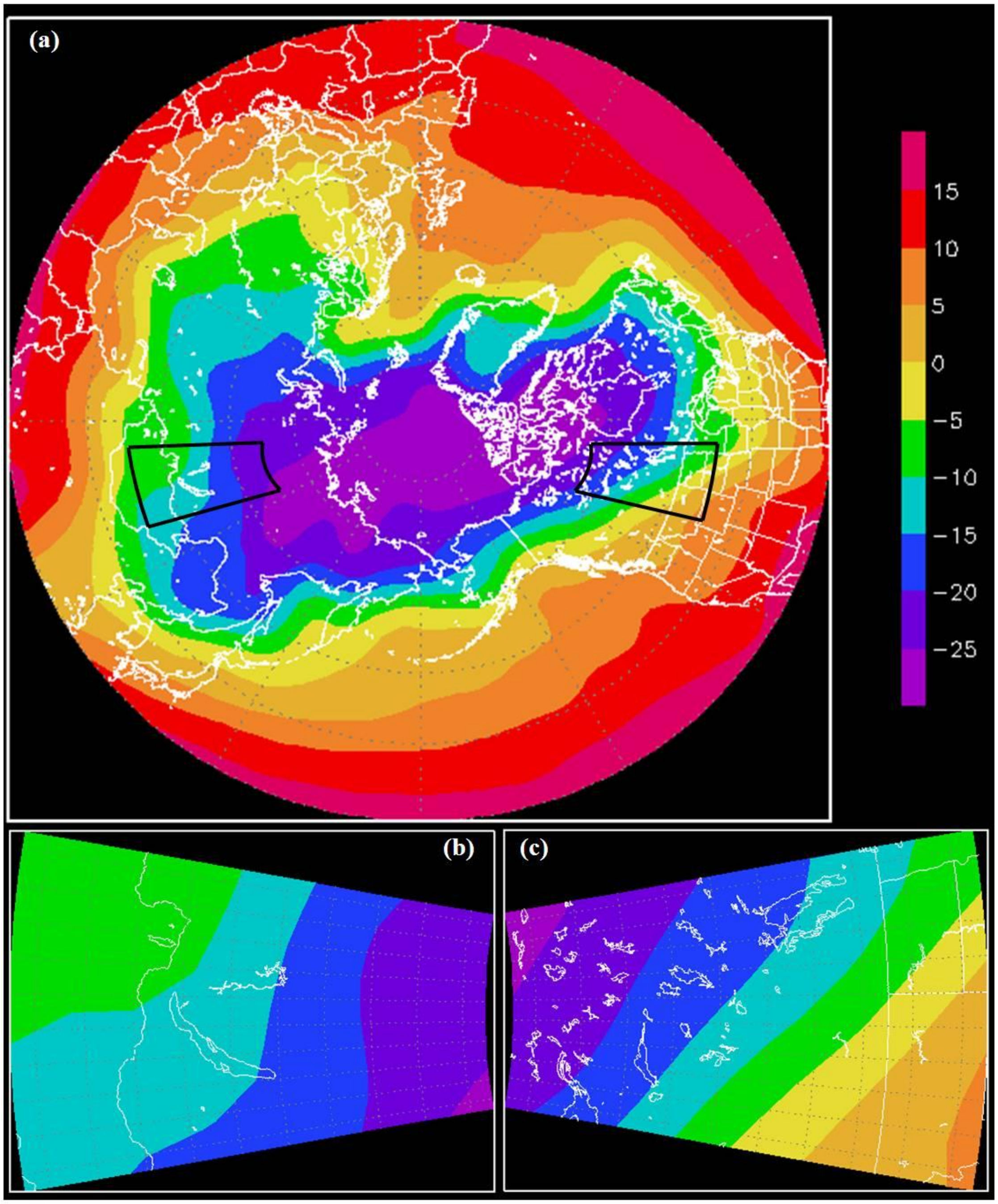


Figure 23: January 29 year average 1000 hPa temperature in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

in the Siberian region and 0.04 °C per year in the Canadian region (Table 7). The Canadian region is colder than the Siberian region six times in the 29 year study period: 1982, 1984, 1994, 1996, 1997, and 2004. The greatest difference occurs in 1984 when the temperature in the Canadian region is 4.7 °C colder than in the Siberian region. There are considerable year-to-year temperature anomalies (Figure 22d). From 1980-1997, the January 1000 hPa temperature anomalies for both regions are in phase for most years, positive or negative at the same time. After 1997, temperature anomalies are less similar, usually with opposite anomalies between regions.

4.a.6.iii. Summary

The largest anomaly change in temperature for the Canadian region occurs from 1981 to 1982 although both years had similar positive MLSP anomalies (Figure 22b and d). This temperature shift could be due to wind direction or moisture advection being distinctly different from just pressure amount from January 1981 to 1982, possibly caused by the high pressure area changing from a dynamically forced system to one dominated by thermodynamic processes. Westerly air flow in the Canadian region would bring air descending out of the Rocky Mountains from a dynamic high pressure system whereas northerly airflow would bring with it colder air from over the frozen Arctic Ocean and a more thermodynamic process.

The largest year-to-year anomaly changes for temperature and pressure in the Siberian region occurs from 2001 to 2002 (Figure 22b and d). Given the geography of the Siberian region (Figure 3), a shift in wind direction would not necessarily bring in very different air masses. Consequently, the correlation between pressure and temperature in the Siberian region seems to be stronger than for the Canadian region. In January 2001, the temperature in the Siberian region is the coldest observed for this study (-19.3 °C) while the warmest Canadian region temperature (-5.2 °C) occurs in the same year (Table 12). This led to a 14.1 °C difference between the two regions, which is the largest monthly value in this study as well. The next year, January 2002, the Siberian region experienced the weakest MSLP (1023.8 hPa) and warmest January 1000 hPa temperature: -8.9 °C. Anomalies in the Canadian region in 2002, however, are close to average and do not experience as large of a change as the Siberian region does.

4.a.7. February Data Analysis: 1980-2008 (seasons of 1979-2007)

4.a.7.i. Mean Sea Level Pressure (MSLP)

The strength of the high pressure center over Asia begins to decrease in February (Figure 24a) while still encompassing more than two-thirds of the Siberian study region (Figure 24b). Although the Canadian region does have high pressure values, the gradient is fairly uniform (Figure 24c). The Siberian region averaged MSLP experiences a declining trend of .11 hPa per year over the study period with an average value of 1027.8 hPa (Figure 25a and Table 7). The Canadian region is also decreasing from an average of 1019.2 hPa, however only a .02 hPa decrease per year (Table 7). February is the winter peak of pressure in the Canadian region, while pressures within the Siberian region are already decreasing from a peak in January. The variability of MSLP in the Canadian region in February is lower than in December by 17% and 27% less than in January (Table 13). February pressure anomalies for the Siberian region follow a pattern

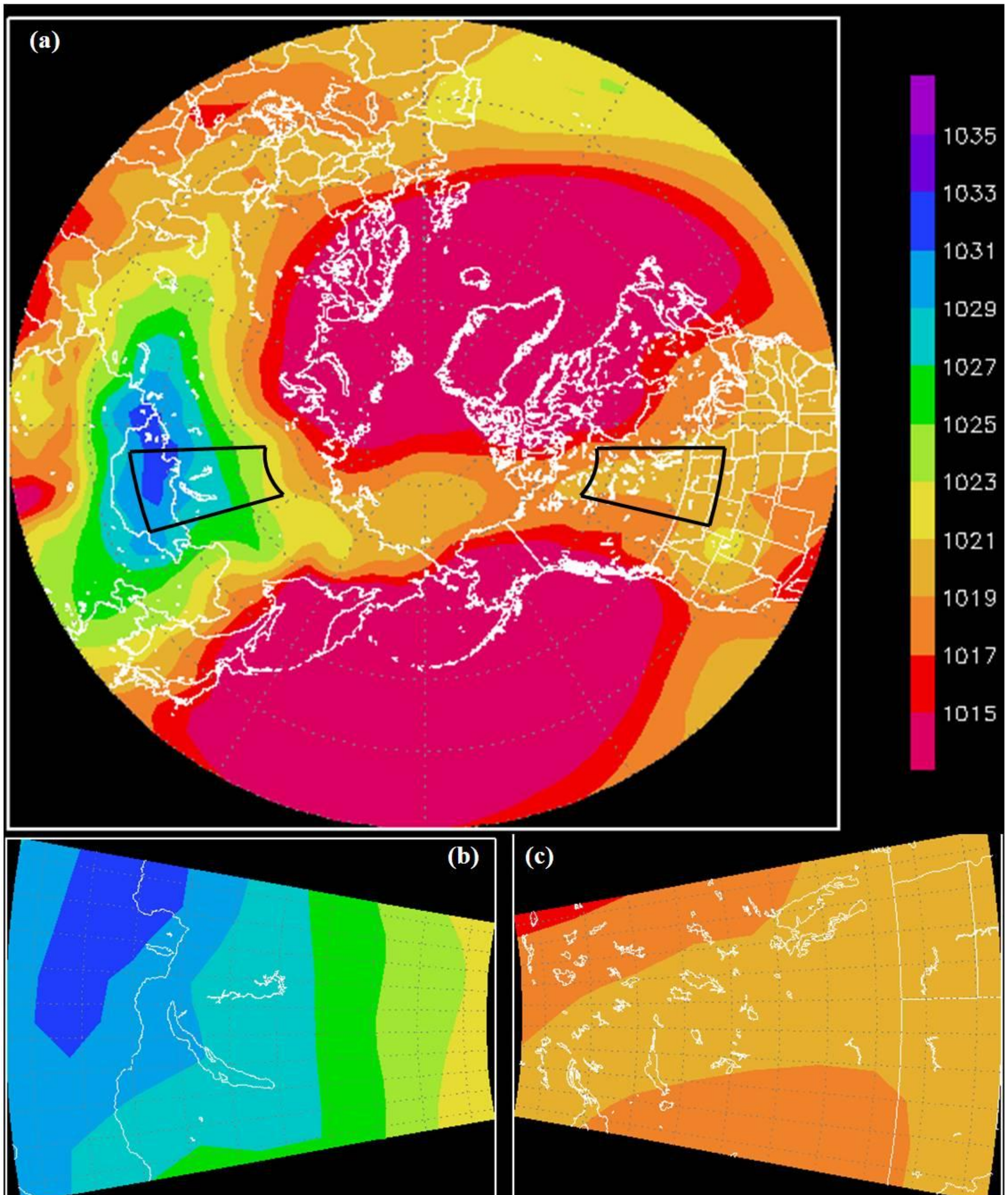


Figure 24: February 29 year average MSLP in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

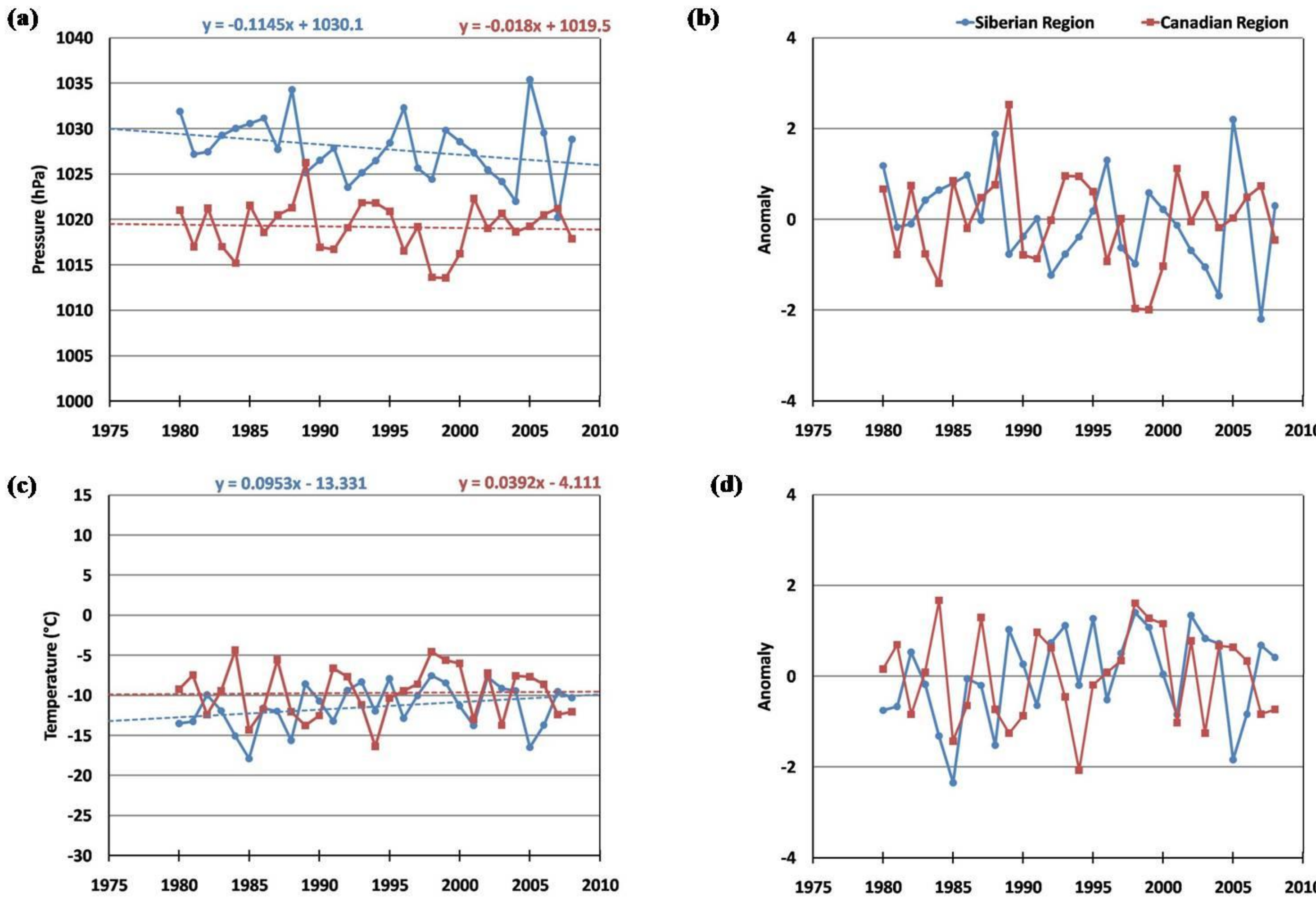


Figure 25: February reanalysis data for (a) MSLP, (b) MSLP anomalies, (c) 1000 hPa temperature , and (d) 1000 hPa temperature anomalies with trend lines plotted for each region.

Table 13: February Data Summary

	Siberian Region		Canadian Region		Difference	
	MSLP (hPa)	**1000 hPa Temp (°C)**	**MSLP (hPa)**	**1000 hPa Temp (°C)**	**MSLP (hPa)**	**1000 hPa Temp (°C)**
Mean	1027.8	-11.4	1019.2	-9.7	+8.6	-1.7
Maximum (year)	1035.4 (2005)	-7.5 (1998)	1026.3 (1989)	-4.3 (1984)	+16.3 (1999)	+5.2 (1989)
Minimum (year)	1020.2 (2007)	-17.9 (1985)	1013.6 (1999)	-16.4 (1994)	-1.1 (1989)	-10.7 (1984)
Range	15.2	10.4	12.7	12.1	17.4	15.9
Std. Dev.	3.5	2.8	2.8	3.2	4.7	4.1

of increasing or decreasing for four or five years in a row followed by a drastic change within one or two years (Figure 25b). Anomalies in the Canadian region, however, vary more from year to year, with the longest sequential trend being only three years long.

4.a.7.ii. 1000 hPa Temperature

The coldest temperatures in northern Asia recede slightly in February (Figure 26a) yet remain anchored over North America. The average February Siberian region 1000 hPa temperature is -11.4 °C and -9.7 °C in the Canadian region (Figure 25c and Table 13), even though temperatures above freezing occur in southern portions of both study regions (Figure 26b and c). While temperatures in the Siberian region are in a warming trend of at 0.10 °C per year, temperatures in the Canadian region have only increased by 0.04 °C per year over the study period (Table 7). The coldest February in 29 years for the Canadian region occurs in 1994 with a temperature of -16.4 °C. The Canadian region temperature is colder than in the Siberian region 10 of the 29 years studied. The greatest temperature difference between regions is 5.2 °C in February 1989, and Canadian region MSLP is also strongest during that month (1026.3 hPa). February is the last month of the climatological winter and there is actually less temperature variability in February when compared to January (Table 12). Both regions have temperature anomalies in phase only 10 of the 29 years studied, indicating a disconnect between the two regions’ temperature anomalies in February (Figure 25d).

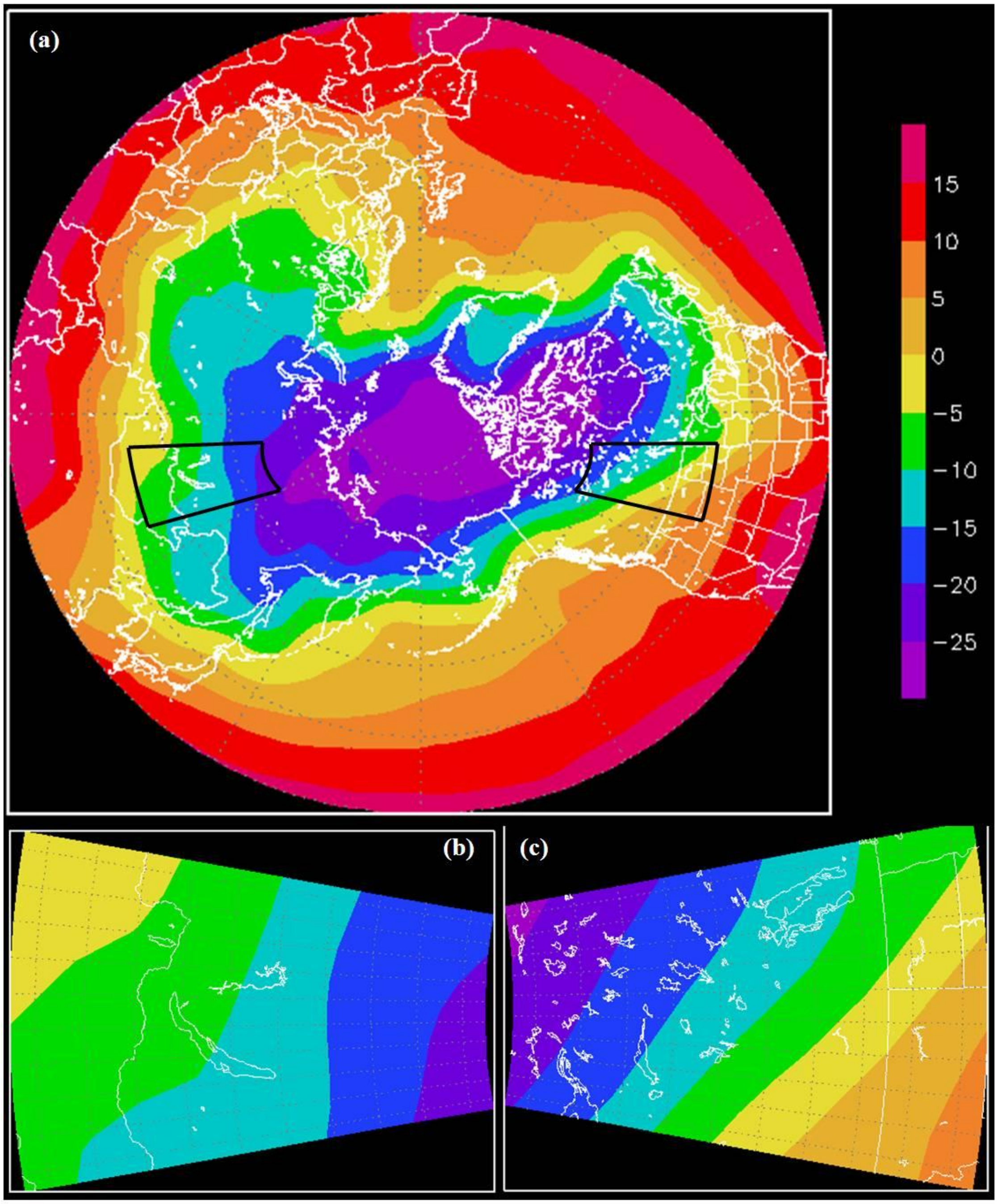


Figure 26: February 29 year average 1000 hPa temperature in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

4.a.7.iii. Summary

Several conflicting situations exist when comparing pressure and temperature anomalies between the two regions (Figure 25b and d). In February 1984, there is a strong positive temperature anomaly and negative MSLP anomaly in the Canadian region with a negative temperature anomaly and positive MSLP anomaly in the Siberian region. When the same positive temperature anomaly occurs in the Canadian region in 1998, this time the Siberian temperature anomaly is also positive. Additionally, both regions have very large negative temperature anomalies in 2001, and there is a positive MSLP anomaly in the Canadian region, yet MSLP is only average in the Siberian region. A negative temperature anomaly would be expected to occur if there is a positive MSLP anomaly. In 2004 the opposite situation occurs, when both regions have similar positive temperature anomalies and there is a negative MSLP anomaly in the Siberian region, yet MSLP is normal in the Canadian region. In these two instances, both regions may have been influenced by different types of high pressure formation.

4.a.8. March Data Analysis: 1980-2008 (seasons of 1979-2007)

4.a.8.i. Mean Sea Level Pressure (MSLP)

March is a difficult month to decipher since it is a transitional month between winter and spring. Areas of high pressure in the Northern Hemisphere rapidly weaken in March although there is still a defined center of high pressure over Asia and a ridge north of Alaska (Figure 27a). High pressure in the Siberian region retracts to the west (Figure 27b) while lower pressures invade the Canadian region from the

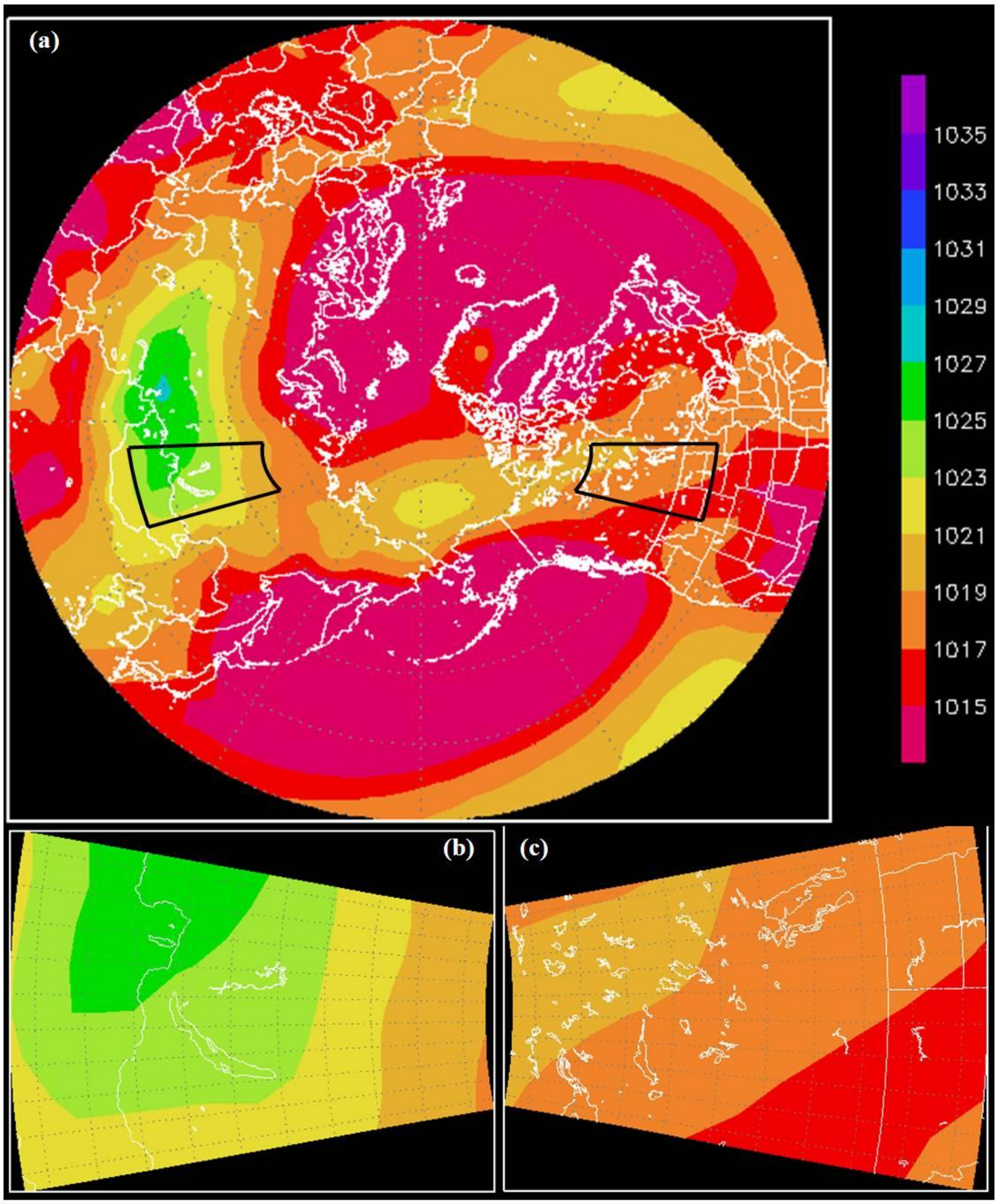


Figure 27: March 29 year average MSLP in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

south (Figure 27c). The average March MLSP in the Siberian region is 1023.1 hPa with a decreasing trend of 0.09 hPa per year (Tables 7 and 14). The Canadian region has an average MSLP of 1018.0 hPa that is increasing by 0.05 hPa per year (Table 7). The strongest March MSLP in the Canadian region is 1023.1 hPa in 1996 (Figure 28a and Table 14). The Canadian region MSLP is stronger than the Siberian region only twice from 1980-2008, by 6.3 hPa in 2002 by 0.6 hPa in 2006. At most, MSLP in the Canadian region is 14.2 hPa weaker than the Siberian region (1991). Both regions only vary by 11 hPa throughout the 29 years in this study, the smallest variability besides October. MSLP anomalies for both regions from 1988-1995 and 2001-2008 behave oppositely, positive in one region while negative at the other (Figure 28b). Anomalies in other years are generally in phase with each other.

4.a.8.ii. 1000 hPa Temperature

By March, the coldest temperatures in the Northern Hemisphere remain primarily over the Arctic Ocean (Figure 29a). A temperature gradient of about 15 °C covers the Siberian region (Figure 29b), while the gradient in the Canadian region is almost twice that amount (Figure 29c). The average 1000 hPa temperatures in March are still below freezing for both regions as winter ends, however, individual years in the Canadian region do get above freezing. The average March temperature in the Siberian region is -4.7 °C with an increasing trend of 0.11 °C per year (Figure 28c and Table 7). The Canadian region is increasing 0.04 °C per year from an average of -4.8 °C (Table 14). Temperatures in March are colder in the Siberian region than the Canadian region only 17 of the 29 years in this study, due to the similarity of the average monthly temperatures.

Table 14: March Data Summary

	Siberian Region		Canadian Region		Difference (S-C)	
	MSLP (hPa)	**1000 hPa Temp (°C)**	**MSLP (hPa)**	**1000 hPa Temp (°C)**	**MSLP (hPa)**	**1000 hPa Temp (°C)**
Mean	1023.1	-4.7	1018.0	-4.8	+5.0	+0.1
Maximum (year)	1027.8 (1980)	0.9 (1990)	1023.1 (1996)	-0.5 (1981)	+14.2 (1991)	+9.7 (2002)
Minimum (year)	1016.5 (2002)	-11.2 (1999)	1012.0 (1991)	-10.8 (2002)	-6.3 (2002)	-9.3 (1999)
Range	11.3	12.1	11.1	10.3	20.5	19
Std. Dev.	2.4	2.9	2.5	2.7	4.1	4.1

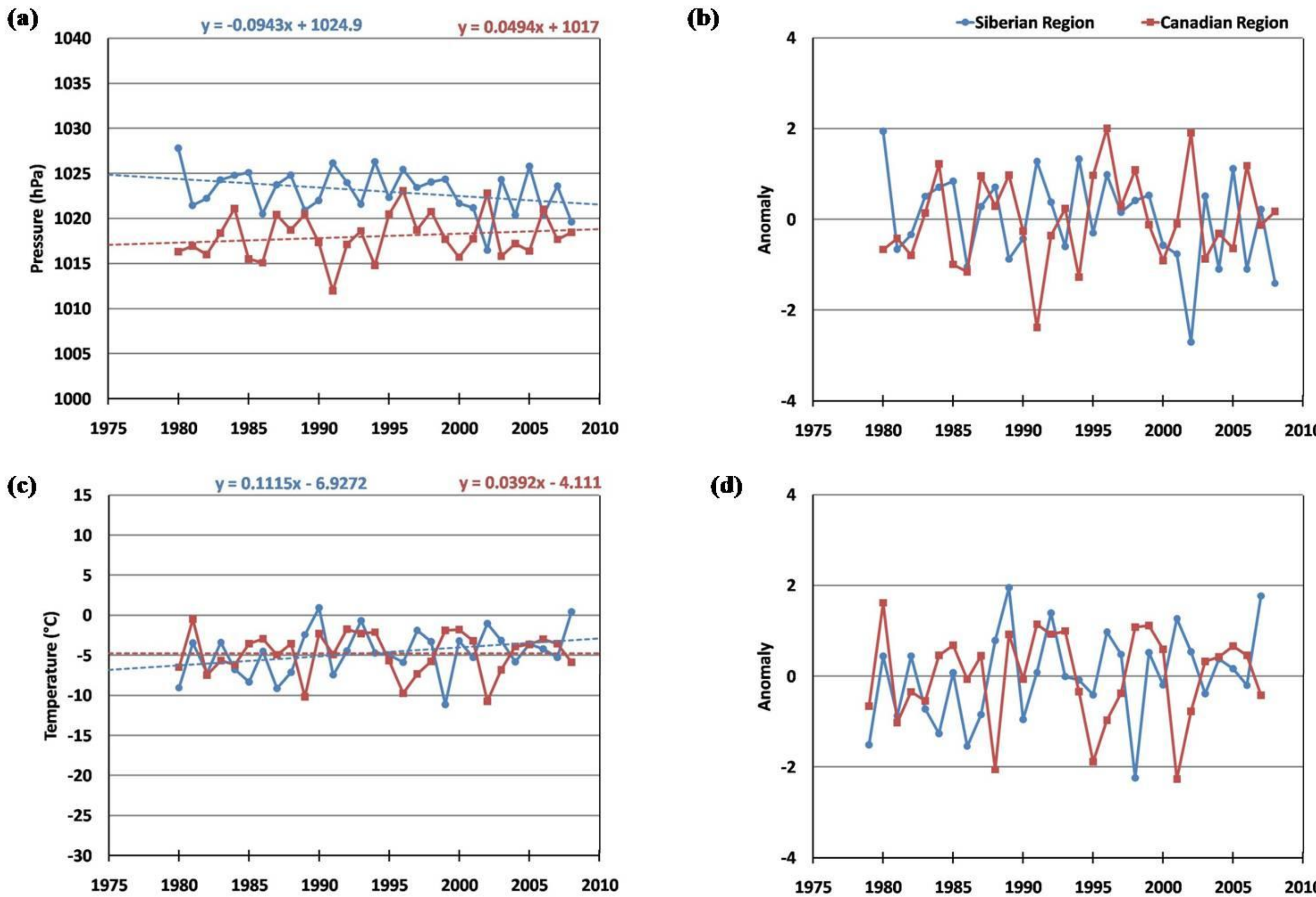


Figure 28: March reanalysis data for (a) MSLP, (b) MSLP anomalies, (c) 1000 hPa temperature , and (d) 1000 hPa temperature anomalies with trend lines plotted for each region.

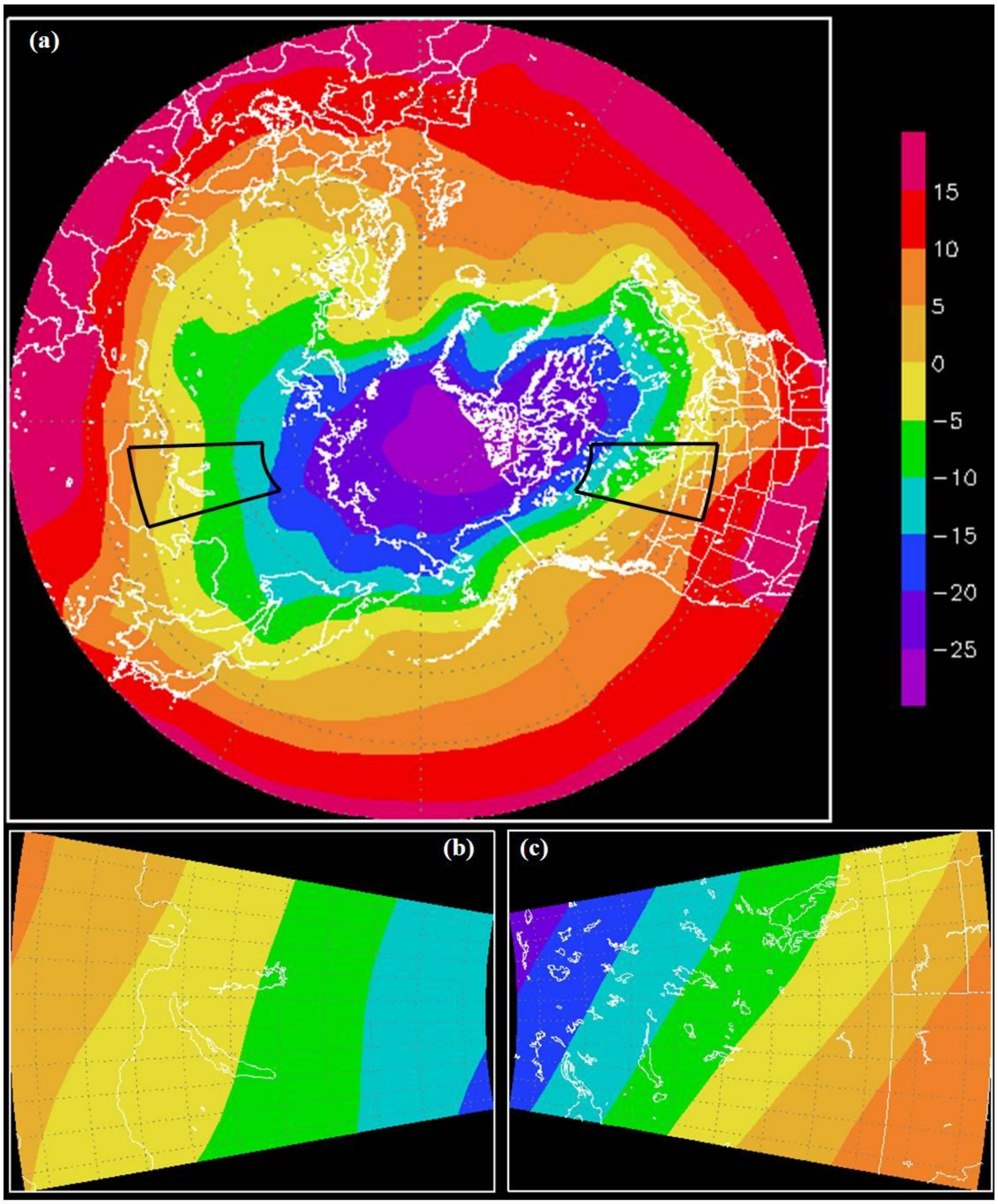


Figure 29: March 29 year average 1000 hPa temperature in the (a) Northern Hemisphere, (b) Siberian Region, and (c) Canadian Region.

In 1999, the Canadian region is warmer than the Siberian region by 9.3 °C. In March 2002, however, the Canadian region is 9.7 °C colder than the Siberian region. This 19 °C range illustrates just how variable temperatures can be in March between both regions (Figure 28c and d). Temperature anomalies for both regions are in phase more than half of the years studied, and out of phase six of eight years from 2001-2008 (Figure 28d). In the Siberian region, March temperatures are the most variable of any month studied with a standard deviation of 2.88 (Table 14). Yet temperatures in the Canadian region are the least variable of any month besides October.

4.a.8.iii. Summary

March MSLP data for the 1980, 1991, 1994, and 2002 seasons have the largest difference in MSLP anomalies between the two regions (Figure 28b). 2002 is the only year of those four that has a stronger MSLP in the Canadian region. Looking at 1000 hPa temperatures in those years, 2002 is the only year that temperatures in the Canadian region are colder than in the Siberian region (Figure 28c), which might be expected due to a negative relationship between pressure and temperature. 2002 is also the only year of those four that has very different temperature anomalies for the two regions. 1980, 1991, and 1994 have very similar anomalies or even no temperature anomalies at all. All of these situations illustrate the complex relationship between MSLP and temperature.

4.b. Control Comparison to Reanalysis

A model control run is run for fifteen years under current atmospheric conditions. This run length allows the model to settle on a yearly pattern for MSLP and 1000 hPa temperature. A single average value for each month from the control is compared with the 29 year reanalysis mean in both regions. This comparison is done to make sure the control run can accurately model current patterns, and if it does, the model inputs can be changed to project climate changes under different forcing environments.

4.b.1. Mean Sea Level Pressure (MSLP)

MSLP values from the control run for the Siberian region start at 1015.7 hPa in October, increase to 1028.9 hPa in January, and decrease to 1023.4 hPa in March (Figure 30a and Table 15). The control is most accurate in modeling pressures from January to March, as it underestimates pressure values by up to 5 hPa for October through December (Figure 31a). The early season (October, November, December) pressure range is 7 hPa, doubling to 14-15 hPa in January and February, and pressure ranges for March are about 10 hPa. Monthly mean values from the reanalysis correlate at .85 with individual monthly MSLP values from the control run, which indicates that the model accurately models the current seasonal pressure cycle (Table 16).

MSLP from the control run in the Canadian region is 1012.8 hPa in October, peaking in January at 1016.4 hPa, and decreasing to 1013.5 hPa in March (Figure 32a and Table 17). A winter MSLP maximum in January does not align with the reanalysis, which has the highest pressures in February. Canadian region MLSP values for October and March are very similar to each other, leading to a symmetrical winter pressure cycle that does not occur in the Siberian region. Monthly pressure ranges for the Canadian region are smaller in October (7 hPa) than all other months, which have ranges of

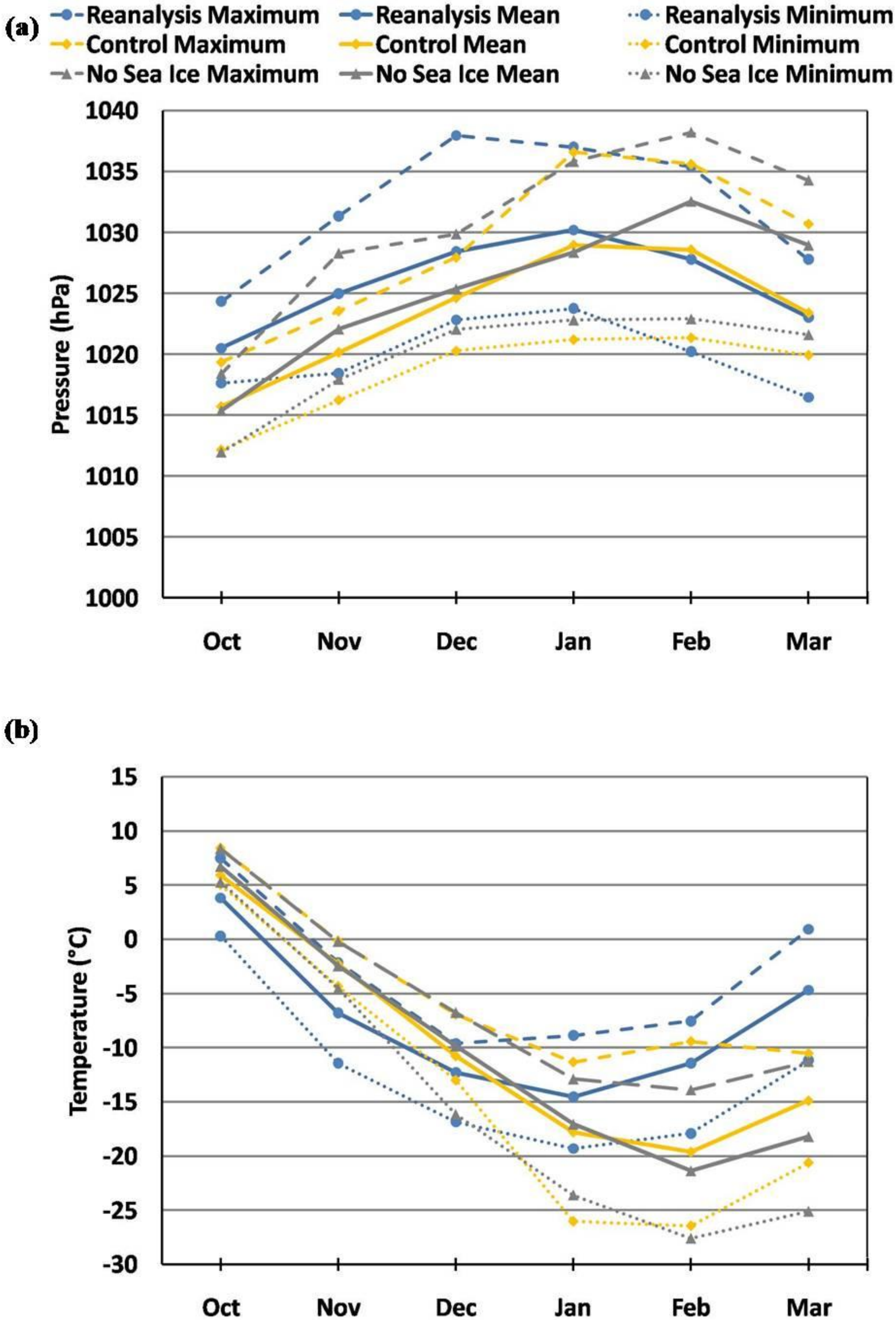


Figure 30: Siberian region comparison for (a) MSLP and (b) 1000 hPa temperature.

Table 15: Control Run Siberian Region Monthly MSLP (hPa)

	Mean	Maximum	Minimum	Range
October	1015.7	1019.4	1012.2	7.2
November	1020.1	1023.6	1016.2	7.4
December	1024.6	1028.0	1020.3	7.7
January	1028.9	1036.6	1021.2	15.4
February	1028.6	1035.6	1021.4	14.2
March	1023.4	1030.7	1019.9	10.8
Winter	1027.4	1030.2	1024.0	6.2

(a)

(b)

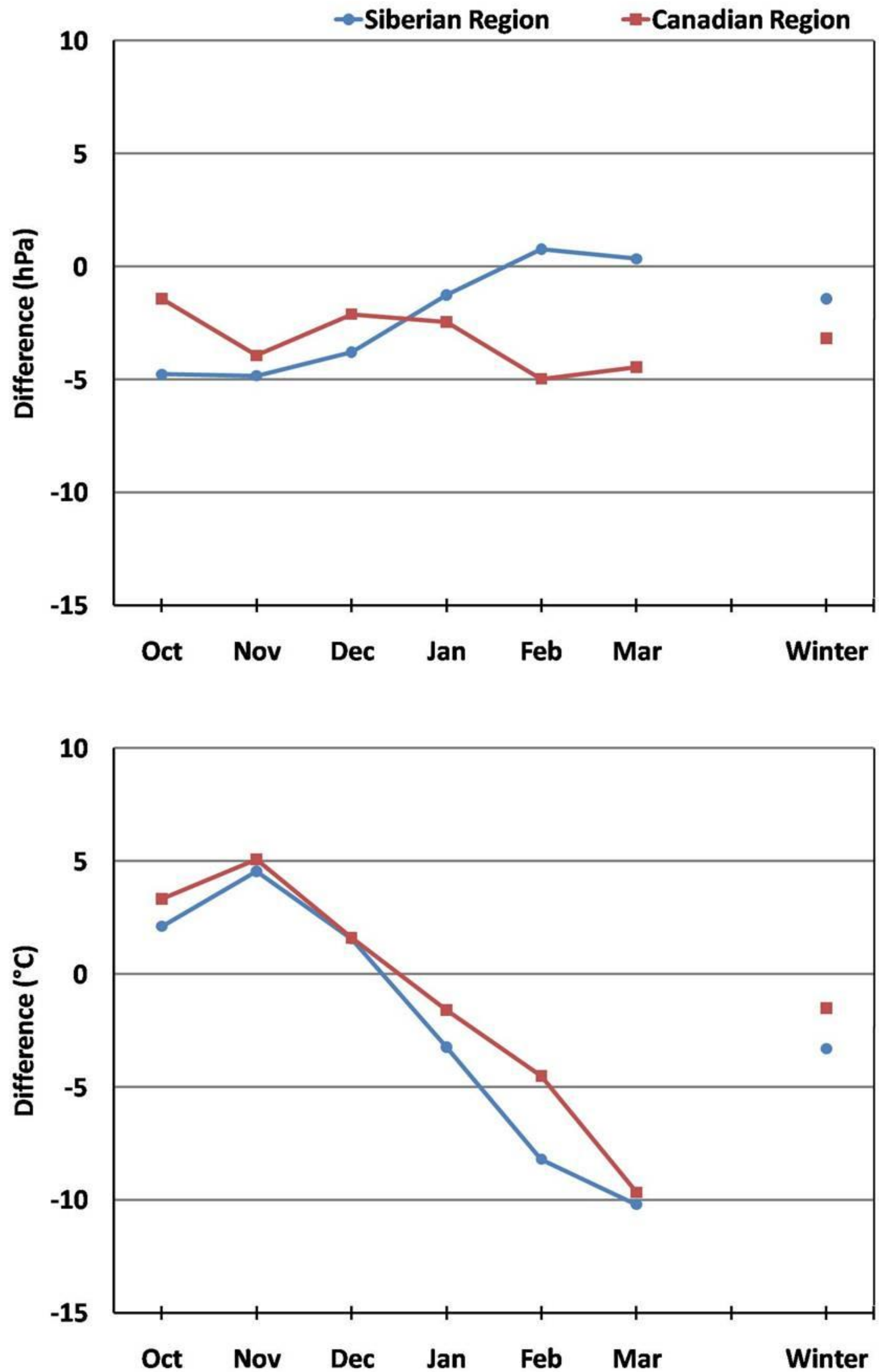


Figure 31: Reanalysis and control differences for (a) MSLP and (b) 1000 hPa temperature.

Table 16: Model Correlations

	Siberian Region		Canadian Region	
	MSLP	**1000 hPa Temperature**	**MSLP**	**1000 hPa Temperature**
Reanalysis vs. Control	0.85	0.83	0.96	0.81
Control vs. No Sea Ice	0.97	0.99	0.95	0.99
Reanalysis vs. No Sea Ice	0.80	0.79	0.95	0.84

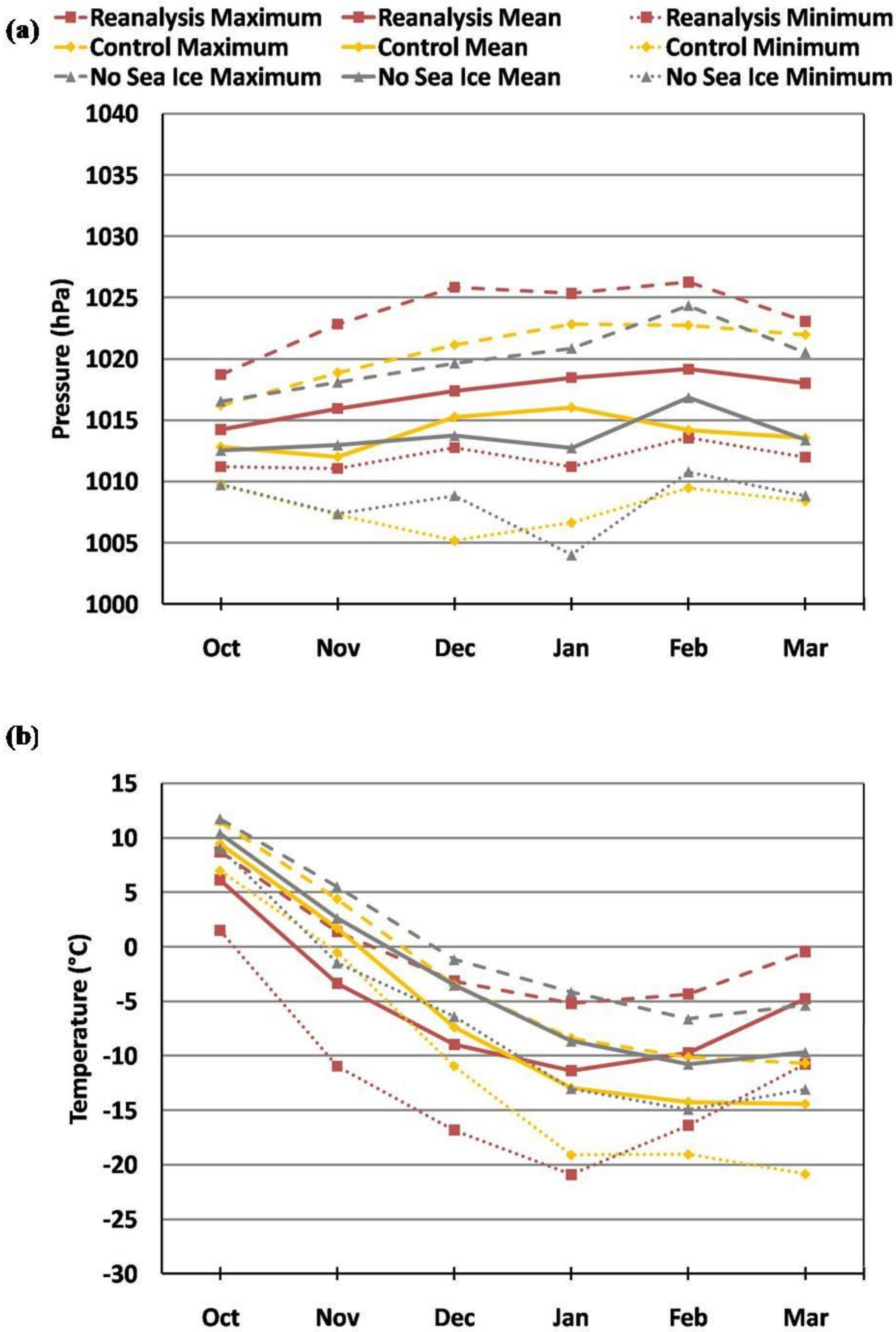


Figure 32: Canadian region comparison for (a) MSLP and (b) 1000 hPa temperature.

Table 17: Control Run Canadian Region Monthly MSLP (hPa)

	Mean	Maximum	Minimum	Range
October	1012.8	1016.2	1009.7	6.5
November	1012.0	1018.9	1007.3	11.6
December	1015.3	1021.1	1005.2	15.9
January	1016.0	1022.8	1006.6	16.2
February	1014.2	1022.8	1009.5	13.3
March	1013.5	1022.0	1008.4	13.6
Winter	1015.2	1020.0	1010.4	9.6

11.6-16.2 hPa from November to March. The control run correlates with the reanalysis at 0.96 for Canadian MSLP data (Table 15), indicating that the general pattern of MSLP behavior is modeled correctly. However, MSLP values from the control are underestimated by 1.5-5.0 hPa throughout the entire extended season (Figure 31a).

4.b.2. 1000 hPa Temperature

The control run for Siberian 1000 hPa temperatures has a tighter range than with its MSLP values (Figure 30b). Siberian temperatures are above 0 °C in October and still very close to freezing in November (Table 18). Temperatures reach their minimum in February and start to increase in March. According to the reanalysis, however, temperatures in the Siberian region are coldest in January, not February. Early season (October, November, and December) temperatures range less than 6 °C each month, while temperature ranges for January, February, and March are 10-17 °C in the control run. These large ranges for late winter temperatures show model uncertainty that is reflected in the correlation between the control and reanalysis (0.83, Table 15). The control overestimates Siberian temperatures from October to December by 2-5 °C and underestimates temperatures from January to March by 3.2 °C under in January, 8.2 °C in February, and 10.2 °C in March (Figure 31b).

According to the control run, temperatures in the Canadian region during October and November are above freezing with the rest of the study period below freezing, and the coldest month is March: -14.4 °C (Figure 32b and Table 19). Temperatures from January to March, however, are within 1.5 °C of each other. For the Canadian region, the

Table 18: Control Run Siberian Region Monthly 1000 hPa Temperature (°C)

	Mean	Maximum	Minimum	Range
October	5.9	8.4	5.0	3.4
November	-2.3	-0.1	-4.3	4.2
December	-10.8	-7.0	-13.0	6.0
January	-17.8	-11.3	-26.0	14.7
February	-19.6	-9.4	-26.5	17.1
March	-14.9	-10.5	-20.6	10.1
Winter	-16.1	-13.1	-19.2	6.1

Table 19: Control Run Canadian Region Monthly 1000 hPa Temperature (°C)

	Mean	Maximum	Minimum	Range
October	9.4	11.5	7.0	4.5
November	1.7	4.4	-0.5	4.9
December	-7.4	-3.5	-10.9	7.4
January	-13.0	-8.4	-19.1	10.7
February	-14.2	-10.1	-19.0	8.9
March	-14.4	-10.7	-20.8	10.1
Winter	-11.5	-9.5	-14.7	5.2

model control run has smaller monthly temperature ranges than the reanalysis: less than 5 °C in October and November and 7.4-10.7 °C ranges from December to March. As in the Siberian region, temperatures in the Canadian region are also overestimated by the control from October to December and underestimated from January to March (Figure 31b). Of any variable investigated by this study, the Canadian region 1000 hPa temperature from the reanalysis correlates the least with the control run (0.81, Table 15).

4.b.3. Summary

Monthly pressure ranges for both regions from the control run are very close to the reanalysis, which indicates that the model control run accurately depicts the formation, strengthening, and weakening of high pressure systems in the Siberian and Canadian regions, even though the control usually underestimates the actual MLSP values. An interesting observation of MSLP when compared between the control and reanalysis is that the control has more accurate MLSP for the Canadian region in the first half of the study period (October to December) yet is more accurate from January to March for the Siberian region (Figure 31a). This mid-season switch raises the question of whether the model control has difficulty resolving pressure values due to the differing orientation of the mountain ranges in both regions, or maybe there is another reason entirely.

Given that early season Siberian pressures are underestimated by the model control run (Figure 31a), it makes sense that the control would overestimate temperatures in early winter (Figure 31b). Since late season pressures are well modeled by the control, having temperatures underestimated is puzzling. If the model develops the high pressure system in Siberia primarily on thermodynamic processes with being less accurate dynamically, this could explain the underestimated temperatures in late winter. The model underestimates both pressure and temperature in the Canadian region from January to March, which could also indicate that the model is not accurately representing the dynamics within the region and thermodynamic processes are more dominant during this period.

4.c. No Sea Ice Comparison to Control

A global climate model is forced with atmospheric conditions with no permanent sea ice in order to model future climate changes associated with global warming and declining Arctic sea ice. The model run lasts for fifteen years, and an average monthly value for MSLP and 1000 hPa temperature is then correlated with values from the model control run.

4.c.1. Mean Sea Level Pressure (MSLP)

When the climate model is run under conditions of no sea ice, MSLP in the Siberian region starts at 1015.4 hPa in October, peaks in February at 1032.6 hPa, and declines in March at 1028.9 hPa (Figure 30a and Table 20). Although February has the strongest pressure value, it is also the most variable month with a pressure range of 15.3 hPa. Siberian pressure ranges for any month in the no ice run were similar to the control run, with the largest ranges occurring from January to March.

Table 20: No Sea Ice Run Siberian Region Monthly MSLP (hPa)

	Mean	Maximum	Minimum	Range
October	1015.3	1018.4	1012.0	6.4
November	1022.1	1028.3	1017.9	10.4
December	1025.3	1029.9	1022.1	7.8
January	1028.4	1035.8	1022.8	13.0
February	1032.5	1038.2	1022.9	15.3
March	1028.9	1034.3	1021.6	12.7
Winter	1028.8	1032.6	1024.6	8.0

A 0.97 correlation between values from the model control run and no sea ice run indicates that the changes predicted by the model are reasonable (Table 15). Without permanent Arctic sea ice, the model predicts less than +/- 2 hPa MSLP difference for the Siberian region from October through January (Figure 33a). Larger differences occur in February and March, with increased MSLP of 4-5.5 hPa. This indicates stronger pressure in the Siberian region, perhaps continuing through what is currently considered early spring. Therefore, according to the model, the effect of not having sea ice produces the unexpected result of longer lasting high pressures in the Siberian region. However, the model could have late winter winds coming from a different direction, from the snow covered west instead of open water to the north. A shift in predominant wind direction could explain the increased and longer lasting high pressure values or a strengthened thermodynamic forcing behind the Siberian high pressure system.

Without permanent Arctic sea ice, Canadian maximum pressure values coincide with the minimum Siberian pressure values (Figure 30a and 32a). The Canadian region has a less pronounced seasonal cycle in MSLP without permanent sea ice, despite the fact that the pressure range is similar to the control run (Table 21). Pressures undergo small oscillations all season, increasing from October to December, dipping slightly in January, peaking again in February before decreasing in March (Figure 32a). Like the Siberian region, the Canadian region October MSLP has a small range (6 hPa). Additionally, the latter stages of winter have the greatest pressure range: between 13.3-16.9 hPa from January to March.

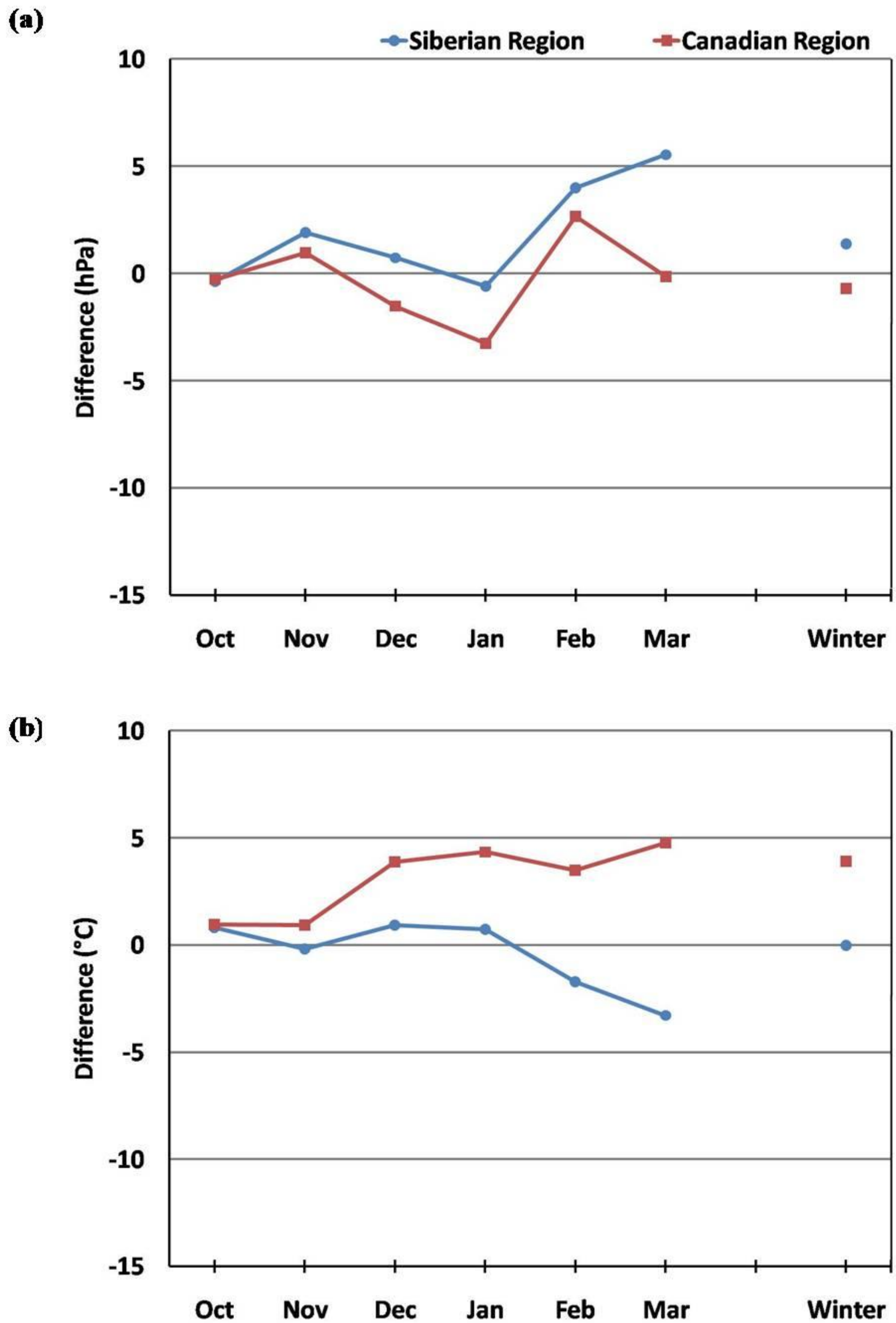


Figure 33: Control and no sea ice differences for (a) MSLP and (b) 1000 hPa temperature.

Table 21: No Sea Ice Run Canadian Region Monthly MSLP (hPa)

	Mean	Maximum	Minimum	Range
October	1012.5	1016.5	1009.7	6.8
November	1013.0	1018.1	1007.4	10.7
December	1013.7	1019.6	1008.8	10.8
January	1012.8	1020.9	1004.0	16.9
February	1016.8	1024.4	1010.8	13.6
March	1013.4	1020.5	1008.9	11.6
Winter	1014.4	1018.0	1010.4	7.6

The correlation is 0.95 between the model control run and no sea ice run for MSLP in the Canadian region (Table 15). Without permanent Arctic sea ice, including Hudson Bay, there is a weakened Canadian high pressure system, mostly due to a less persistent high pressure system with more month-to-month fluctuations (Figure 33a). According to the no sea ice run, the transition into and out of winter (October-November and March) do not have different pressure values from the control run. It is during the actual winter months when pressures are weaker in December and January and stronger in February with open water on the Arctic Ocean and Hudson Bay.

4.c.2. 1000 hPa Temperature

Just as the MSLP peaks in February for the Siberian region, the coldest temperatures also occur in February: -21.4 °C (Figure 30b). October remains the only month with temperatures above freezing (Table 22). 1000 hPa temperatures in October and November only range 3-4 °C, December and January range 9-10 °C, however, temperatures in February and March can range as much as 14 °C from model run year to run year. Therefore, the model is certain on early season temperatures in the Siberian region, and has more difficulty with the middle and ending stages of winter.

A correlation of 0.99 between the control and no sea ice run should lead to confidence in the 1000 hPa temperature changes predicted by the model (Table 15). October is still the only month with above freezing 1000 hPa temperatures, even without Arctic sea ice. Compared to the control run, the no sea ice run temperatures in the Canadian region in October, December and January are about 1 °C warmer and 2-3 °C

Table 22: No Sea Ice Run Siberian Region Monthly 1000 hPa Temperature (°C)

	Mean	Maximum	Minimum	Range
October	6.7	8.4	5.3	3.1
November	-2.4	-0.2	-4.6	4.4
December	-9.8	-6.8	-16.2	9.4
January	-17.1	-12.9	-23.6	10.7
February	-21.3	-13.9	-27.6	13.7
March	-18.2	-11.3	-25.1	13.8
Winter	-16.1	-12.8	-19.5	6.7

colder in February and March (Figure 33b). This result is surprising, since one would expect warmer temperatures in an environment with open ocean water all winter long.

According to the model run without sea ice, Canadian region 1000 hPa temperatures are above freezing in October and November, and temperatures in February are the coldest temperatures of winter (Figure 32b). Minimum temperatures in February match up with the MSLP maximum for the same month (Table 21). The most temperature variability for any winter month is 8.8 °C in January, and all other monthly temperatures vary less than that (Table 23).

The no sea ice run correlates with the control at 0.99 for the Canadian region (Table 15). Similar to the Siberian region, temperature ranges in the Canadian region are small at the beginning of winter (October through December) and larger from January to March (Table 23). In the no sea ice run, October to December temperatures should not have large differences from the control given since sea ice is usually forming during this time. However, larger changes from January to March should occur in the no sea ice run since the model does not allow ice to form in those months. These differences are reflected in the temperature ranges from October to December with respect to January to March. Temperatures from the no sea ice run are higher than in the control run for every month studied, by about one degree in October and November and about 3.5-5 °C warmer from December to March (Figure 33b), which would be expected under a warmer climate with no sea ice.

Table 23: No Sea Ice Run Canadian Region Monthly 1000 hPa Temperature (°C)

	Mean	Maximum	Minimum	Range
October	10.4	11.7	9.0	2.7
November	2.6	5.5	-1.5	7.0
December	-3.5	-1.2	-6.4	5.2
January	-8.6	-4.2	-13.0	8.8
February	-10.7	-6.6	-14.9	8.3
March	-9.7	-5.3	-13.1	7.8
Winter	-7.6	-5.0	-10.1	5.1

4.c.3. Summary

The coldest Canadian region temperatures match almost exactly with the warmest Siberian region temperatures in the no sea ice model run (Tables 22 and 23). This relationship is consistent with maximum Canadian region pressures being the same as low Siberian region pressures (Tables 20 and 21). Smaller monthly temperature ranges in the no sea ice run with respect to the control indicate a thermal buffer from the open water on the Arctic Ocean and Hudson Bay for the Canadian region (Tables 19 and 23). Additionally, smaller monthly temperature ranges in the Canadian region when compared to the Siberian region could be due to either different mountain range orientation or having large neighboring water bodies near two boundaries of the region as opposed to only one region boundary in the Siberian region.

Although the no sea ice model run produces opposite patterns in MSLP and temperature for both regions, the opposite patterns could be due to thermodynamic forcings in the atmosphere. If the air in Siberia is colder, it becomes denser and therefore exerts a higher pressure near the surface. In Canada, however, warmer air due to open seas will expand the air column near the surface and create lower pressures. Dynamic forcings could also be playing a role in the differences between the two regions.

Chapter 5. Conclusions

Analyzing the reanalysis data confirms an inverse relationship between temperature and pressure in the Siberian and Canadian regions. Overall, MSLP values are greater and temperatures are colder in the Siberian region when compared to the Canadian region. Maximum pressures in the Siberian region occur in January while pressures do not peak in the Canadian region until February. However, the coldest temperatures of winter occur in January for both regions. Variability for pressure and temperature is lowest in October, peaks in January or February, and slowly decreases thereafter.

Usually, a positive [negative] pressure anomaly is accompanied by a negative [positive] temperature anomaly, which is most likely caused by a thermodynamic formation of pressure systems in the areas. However, there are instances when anomalies of the same sign occur for both pressure and temperature, which could result from a more dynamic synoptic pattern as opposed to thermodynamically controlled. Even so, anomalies of pressure and temperature do not necessarily match between the Siberian and Canadian regions. There are years when both regions have positive MSLP anomalies and negative temperature anomalies, or one region's anomalies could be completely opposite and out of phase with the other region. Whether the anomalies are in or out of phase between regions could be due to whether the ridge or trough pattern of the planetary scale Rossby waves are in phase for each region. There does not seem to be any changes in the magnitude of pressure or temperature anomalies between months or over the 29 year study period.

A minimal increasing trend in MSLP in the Siberian region found by this study does not agree with the results of Panagiotopoulos et al. (2005), who found a sizeable MSLP decrease. However, several differences between the studies themselves could account for the difference. Panagiotopoulos et al. (2005) used multiple datasets with inconsistent data records for a different study period and a larger geographical region than this study. These differences alone make it difficult to compare the results of both studies regarding MSLP trends within a Siberian region.

The seasonal patterns and monthly ranges for MSLP and 1000 hPa temperature are similar between the reanalysis and computer model control run, however, the control run underestimates MSLP for both regions. From October to December, MSLP values from the control are closer to the reanalysis for the Canadian region, yet from January to March the control run MSLP are closest to the reanalysis for the Siberian region. Early season (October to December) temperatures are overestimated by the control run by up to 5 °C while temperatures from January to March are underestimated by 5-10 °C.

It is logical to assume that without permanent Arctic sea ice, winter temperatures should increase and MSLP would decrease. Results from the no ice model run produce puzzling results for the Siberian region. According to the no sea ice run, MSLP in the Siberian region peaks later and does not decrease as fast as in the control run. In addition, temperatures in the Siberian region are slightly warmer in the first part of winter yet colder in February and March. High pressures in the Canadian region are less persistent, with more month-to-month fluctuations and warmer temperatures for the entire extended period. Decreasing MSLP and increasing temperatures for the Canadian region seem sensible and are what one might expect in an environment with no sea ice.

Perhaps the differing orientation of mountain ranges in both regions could account for some of the different conditions from the no ice model run. For instance, the mountains on the southern edge of the Siberian region can prevent warmer air from entering the region from the south and dam up the colder air from the north. On the other hand, the mountain range in the Canadian region is on the western boundary, so warmer air from the south is free to move north, and the cold Arctic air is not trapped in the region as it is in Siberia.

The model seems to favor a thermodynamic forcing to high pressures in the Siberian region in the no sea ice run, with higher late winter pressures and colder temperatures (Figure 33). A thermodynamic forcing, as opposed to dynamic, also seems to appear in the Canadian region. The no sea ice run produces mostly lower pressures and warmer temperatures than the control run. Under primarily dynamic forcings, higher pressures would lead to warmer temperatures due to the adiabatic warming of descending air from aloft, and lower pressures would lead to colder temperatures due to ascending and cooling air above the surface.

Understanding what influences current anomalies in MSLP and temperature is important for future work. Using only two variables is a starting point, and investigating other atmospheric variables may reveal the intricacies of a relationship between the two study regions. Using thermodynamic or dynamic forcings as variables influencing MSLP and temperature relationships would also be beneficial in understanding the complexity of these hemispheric patterns. While the Arctic Oscillation is used minimally by this study, understanding the role of several other hemispheric teleconnection patterns could also shed light on the main source of MSLP and temperature variability in Northern Hemisphere winters. Once the cause and effect relationship is further elaborated and current patterns are understood better, it should be easier to predict future changes in MSLP and 1000 hPa temperature.

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